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Minimizing Life-Cycle Costs of Gun Propellant Selection Through Model-Based Decision Making: A Case Study in Environmental Screening and Performance Testing

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Minimizing Life-Cycle Costs of Gun Propellant Selection Through Model-Based Decision Making: A Case Study in Environmental Screening and Performance Testing

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Abstract

This work demonstrates the first phases of a newly proposed gun propellant formulation process that will minimize life-cycle costs through science-based design. This new approach proposes maximal use of modeling and simulation in the earliest phases of the developmental cycle to screen candidate formulations, resulting in elimination of probable poor performers and identification of the most promising test candidates. The screening and identification of propellant formulations are demonstrated under the assumption of a specific weapon platform and user requirements. The process of selecting a propellant for the assumed gun system application has been distilled into measurable steps, leading from a set of candidate materials, through logical and numerical filters, to a shorter list of energetic materials demonstrated as viable weapon platform choices. Environmental filtering and performance modeling are used to screen propellants through a well-defined sequence of tests designed to weed out materials not meeting safety, energy, or manufacturability standards. Because much of the testing is performed by computer modeling, the gun systems and energetic materials need not be present (or even existent) in order to be described and matched against performance requirements for future applications. The calculations demonstrate that utilizing computer models rather than physical testing in the early developmental stages of the formulation process can produce enormous savings in labor, material, and environmental costs, along with a tremendous reduction in the time required to select a "best candidate" propellant.

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1. Introduction

The attainment of proposed future war-fighting capabilities [1] will depend on the performance of new weapons platforms and the energetic materials that are used by them. In order to efficiently and effectively meet the requirements of the future weapons systems, a mechanism must be in place for the rapid design and manufacture of advanced chemical fuels. Presently, there is no single formal procedure in place for the design and development of a new propellant; rather, the overall procedure includes any number of steps leading to deployment of a new energetic material. The inclusion of steps varies among individuals according to experience, philosophy, and training. Also, the overall procedure relies heavily on experimentation and measurement and often proceeds through lengthy cut-and-try processes. Significant waste streams in terms of time, manpower, and materials are generated from implementation of such unstructured developmental procedures, and they often exact unacceptably large time and environmental penalties. Current fiscal realities and increased environmental constraints necessitate a revision in existing strategies for energetic material design, development, and manufacture. The most obvious revision that must be made is to minimize the waste created during the process. In order to do this, a formal mechanism must be established to estimate the waste associated with each part of the procedure and, thus, assign costs to each step in the mechanism. The assignment of costs will depend upon the priorities that drive the development of the material and could include pecuniary, environmental, or performance considerations. Then refinements to the steps and overall mechanism can be made to minimize the cost and maximize the efficiency of the process.

The Strategic Environmental Research and Development Program (SERDP), in recognizing the need to counter extreme waste generation in energetic materials development, is supporting a project whose goal is to establish a new developmental procedure that will minimize waste generation throughout the entire process. The project is currently limited to gun propellant formulations; however, the same developmental procedures could be applied to other classes of energetic materials, including rocket propellants, explosives, or pyrotechnics. The developmental procedure that is being advanced under this project is model-based. In other

words, the goals of the project can ideally be achieved through replacement (where possible) of measurement and testing with computer modeling or through optimal reduction of experimentation by the exercise of predictive methodologies. This new approach to gun propellant formulation is outlined in a parallel report [2] that describes a science-based activity where the earliest possible steps utilize modeling and simulation of all stages that might occur during development of a gun propellant. Although modeling of the complete process cannot be implemented at this time since there are several areas in which models do not currently exist, the work described here is an attempt to exercise the developmental procedure using available models.

Part of the propellant assessment involves determination of whether its performance in a cannon will meet the military requirements of projectile velocity (which governs effective range of the weapon) within the limitations of pressure and acceleration peculiar to the gun system and projectile. Predictive performance models [3–5] have been available in the military for many years and are well-suited for computing expected solutions of the interior ballistic cycle for known (measurable) guns and for gun systems as yet only imagined. These computer models require *a priori* information describing the physical parameters of the gun chamber and tube, of the projectile, of the propellant charge, and of critical interactions during the gun firing. This report explains how to use available computer programs to model the performance testing of a proposed set of gun propellants in a large-caliber artillery weapon. Additionally, since the proposed developmental approach incorporates environmental screening procedures at each stage of the development process, we have attempted to include such in our demonstration. A prototypical simulation was performed in which minimal user requirements for maximum pressure and minimum muzzle energy were assigned for a specific weapon platform using a set of 10 existing propellant formulations. Using performance modeling and database information on environmental hazards, 6 of the 10 formulations were eliminated as candidates due to environmental constraints and failure to meet energy requirements. This demonstration shows that application of computer models based on scientific principles during gun propellant design and formulation will result in cost savings through decreases in labor, equipment, and environmental issues.

2. Performance Testing Description

2.1 Propellant Database. A generalized flow chart of the necessary steps in testing the performance of a new gun propellant is shown in Figure 1, representing the early screening steps of the science-based design process outlined in the study of Miller, Rice, and Cramer [2]. The Master Optimization Algorithm (MOPTA) starts with a database of new and/or known propellants to be tested and screened for suitability to a "virtual gun system." This gun system may be a computer model of a known weapon or a model of a completely theoretical gun system to be analyzed for possible manufacture and deployment. From its chemical and thermodynamic description, each propellant is to be characterized in the weapon without ever having physically been placed in the chamber, or perhaps without ever having been actually created in a laboratory. The portion of the algorithm to be described in this report is highlighted with a gray background in Figure 1—the other blocks contain steps where either models are not yet available or else the authors do not have the expertise necessary to use current programs or databases.

2.2 Ingredient Environmental Screening. Those propellants containing known environmental hazards may be screened out of the performance testing process here. Legacy propellants may include ingredients that have been identified, in the years since original production, as carcinogens or as substances toxic to one or more environmental systems. This could include not only the ingredients themselves but also the manufacturing processes involved in creating the material.

2.3 Thermodynamic Properties. Each propellant must be described by a suite of measurable physical parameters in order to be acceptable to the interior ballistic (IB) computer programs. Required values include isochoric flame temperature, density, internal chemical energy, and others depending on which computer code will be used for performance modeling. Several programs are available to estimate these parameters (except for density and burning rate) from the initial chemical description. These programs include CHEETAH [6], BLAKE [7], and TRAN72 [8] and CEA [9]. Part of the output generated by these codes can include a list of combustion products (both gaseous and condensed), which can be scanned to determine

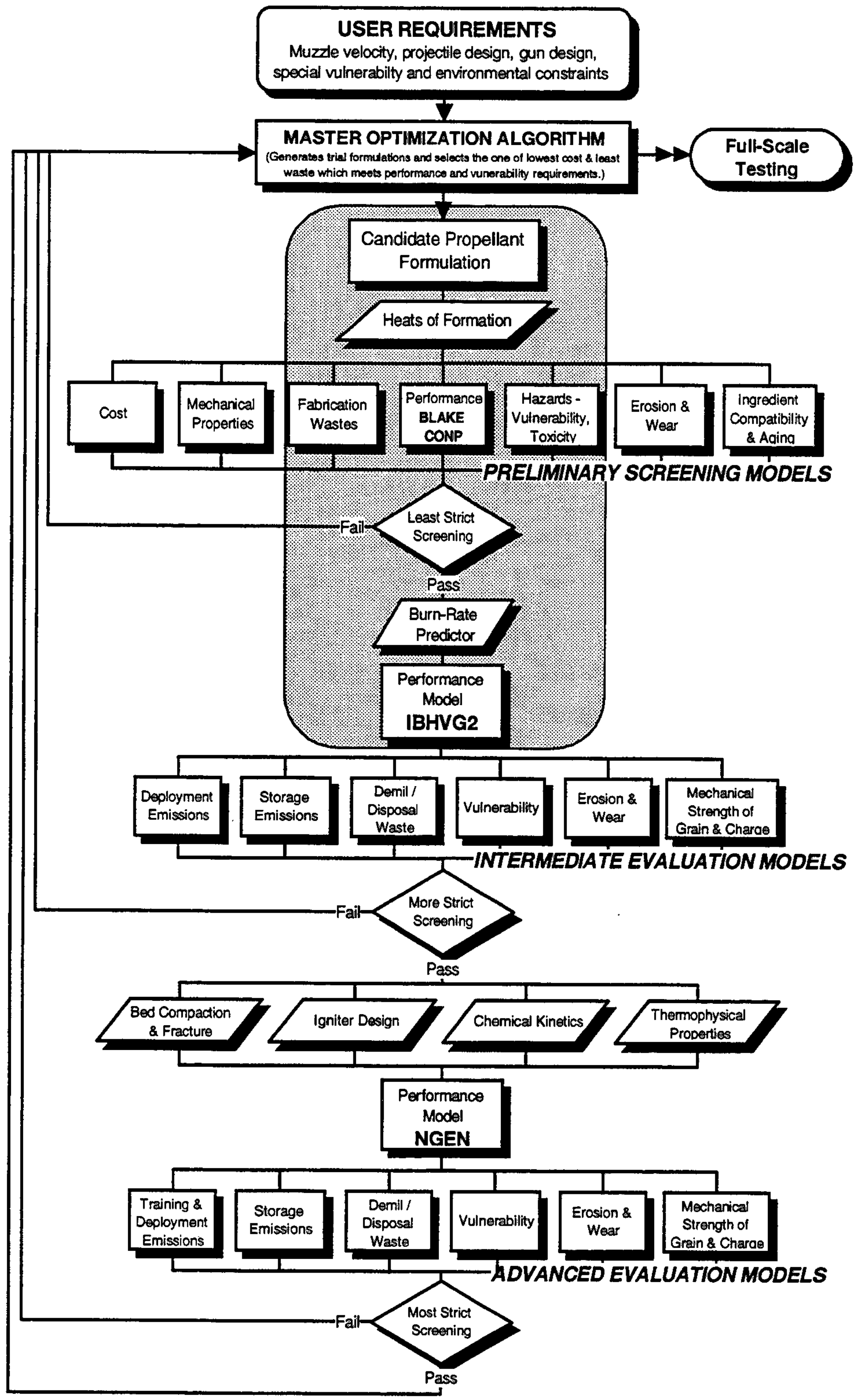

Figure 1. Master Optimization Algorithm.

if toxic or corrosive materials are predicted. Propellant density and burning rates must be physically measured or estimated from other sources.

2.4 Estimate of Available Energy. Given a gun system model and the thermodynamic properties of each propellant, an estimate can be made of how much energetic material can be placed in the gun chamber. A calculation can then be made to determine if enough kinetic energy can be transferred to the projectile in order to meet the exit velocity requirements. By assuming that the highest allowable pressure is continuously maintained by propellant combustion (until the charge is exhausted), an estimate of maximum achievable projectile exit velocity can be calculated. If this velocity does not meet or exceed user requirements, then the propellant will not be a candidate for further testing. Computer codes that can estimate this maximum are IBHVG2 [10] and CONPRESS [11].

2.5 Propellant Grain Geometry. Actual energy transferred to a projectile will be somewhat less than that calculated in the previous step because propellant grain design cannot provide a continuous, unwavering pressure level for the life of the burning charge. Standard grain geometries (19-perf, 7-perf, and single-perf, shown in Figure 2) can be parametrically computed and tested within the gun system model. In general, a multiperforated grain design is more efficient in transferring energy to a projectile; this rule of thumb may be untrue for certain "virtual" gun systems where databases may be varied to experiment with nontraditional dynamics in chamber sizes, projectile/bore interactions, and other physical parameters. Interior ballistic calculations can determine if one or more propellant grain designs used as charges in the real (or future) gun system can meet requirements for muzzle energy and complete charge burnout within maximum pressure limitations. A first-pass IB program is IBHVG2; if predictions of pressure waves within the gun chamber are required, then XNOVAKTC [12] or NGEN [13] may be used.

2.6 Low-Zone Charge Applications. Artillery guns are routinely loaded with a less-than-maximum charge when targets are located at relatively short ranges. These "zoned" applications allow optimum trajectories for higher kill probabilities. Lowest-zoned charges are

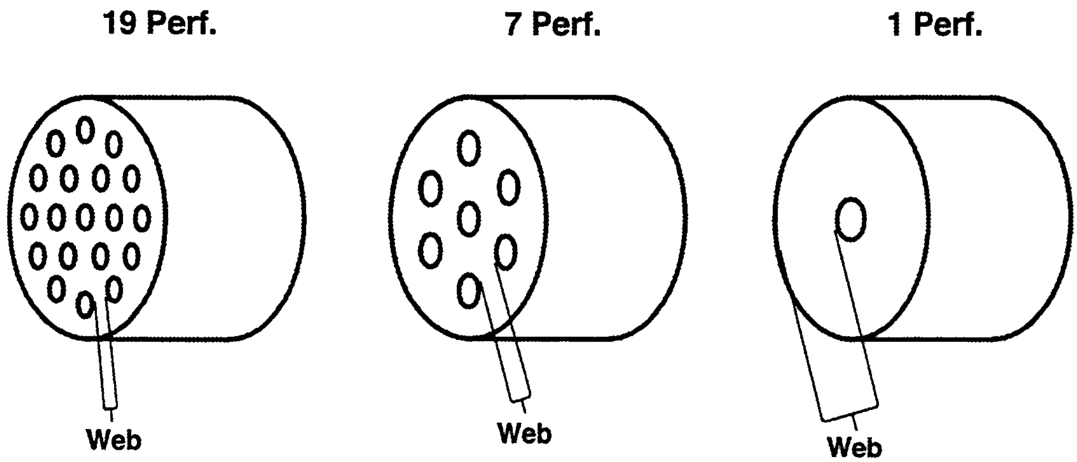

Figure 2. Propellant Grain Types.

still required to burn completely before the projectile exits the gun muzzle; unburned and partially burned propellant particles and gases can be major causes of secondary muzzle blast and flash. If low-zone applications are defined, then the grain geometry meeting minimum energy requirements at maximum charge weights must still show complete burnout when used at lower loading densities. The same IB programs that previously calculated acceptable propellant grain geometries may also be used here.

2.7 Propellant Suitability. Other conditions may screen out propellants that meet muzzle energy requirements. Cost, manufacturing limitations, burning temperature (a major factor in gun tube life expectancy), grain size, or any number of user-defined stipulations may preclude propellants from final consideration. More likely, the list of remaining propellants will be ranked according to importance of these additional factors.

3. Example Performance Screening

3.1 User Requirements. As a test system, the Navy 5-inch 54-caliber gun was chosen to be the vehicle for exercising the propellant performance analysis. User-supplied guidelines included a maximum pressure limitation of 65 ksi (448 MPa) and a minimum muzzle energy of

18 MJ with a 110-lb (49.9 kg) projectile. From the kinetic energy formula ($KE = \frac{1}{2} MV^2$), it can be determined that projectile velocity needs to be at least 848 m/s to meet the requirement. A general description of the weapon specifies a chamber volume of approximately 0.0151 m^3 (919 in^3) and a projectile travel of 6.84 m (269 inches).

3.2 Propellant Database. A mixture of old and new propellant formulations, from both Army and Navy sources, provided a well-rounded sample for the analysis. All propellants are real—no theoretical materials have been added to the study, although it certainly could be done in further tests. The standard Army propellants include M1, M10, M26E1, M30A1, M31E1, and JA2; Navy propellants are NACO, EX99 (called LOVA in the reference noted in Table 1), HELP42, and BAMO/AMMO (abbreviated as BAMO in the rest of this report). No particular method was used for propellant selection other than an attempt to include the several classes (single-base, double-base, and triple-base propellants), along with some newer formulations not fitting neatly into such descriptions.

3.3 Ingredient Environmental Screening. Table 1 shows the proposed propellants and lists their ingredients. A quick scan reveals that NACO contains lead carbonate (Pb_2CO_4)—a known toxic substance and suspected carcinogen [14]. For this reason, NACO was dropped from further analysis. (If a cost of manufacture with suitable biohazard controls and increased demilitarization expenses would be computed, then such a material could be included in the complete performance appraisal; the extra factors would be added to a final figure for overall life cycle costs.)

Dinitrotoluene (DNT) is an ingredient of the Army M1 propellant. The International Chemical Safety Card (ICSC 0727) [15] describes this substance as able to be absorbed through human skin and ingested through inhalation of fumes when it is heated. For humans, it is an irritant to the eyes and skin and may cause effects on the central nervous system, cardiovascular system, and blood. It is also extremely toxic to aquatic organisms. The environmental costs from DNT can be very high; as an example of the type of chemical ingredient to be avoided, mixtures with DNT (specifically M1) will be removed from the list of propellants under consideration.

Table 1. Ingredients of Propellants

Propellant	Ingredients	Reference
M1	NC1315 DNT DBP DPA H2O ALC	Freedman [16], p. 121
M10	NC1315 DPA KS H2O ALC	Freedman [16], p. 121
M26E1	NC1315 NG EC H2O ALC C	Freedman [16], p. 122
M30A1	NC1260 NG NQ EC KS ALC C	Freedman [16], p. 122
M31E1	NC1260 NG NQ DBP NDPA KS ALC C	Freedman [16], p. 122
NACO	NC1200 BS EC KS PB2CO4 H2O ALC	Freedman [16], p. 122
JA2	NC1304 NG DEGDN AKAR2 MGO H2O C	Miller [17]
BAMO	RDX BAMO AMMO	Almeyda [18]
HELP-42	HZTZ RDX NC1260 BDNPF BDNPA EC	Cramer [19]
EX-99	RDX NC1260 CAB BDNPF BDNPA EC	Cramer [19]

The ingredient definitions in Table 1 and in text are as follows:

- AKAR2 Akardite II
- ALC Ethanol (ethyl alcohol)
- AMMO Azidomethylenemethyl oxetane
- BAMO Azidomethyl oxetane
- BDNPA Bisdinitropropyl acetal
- BDNPF Bisdinitropropyl formal
- BS Barium sulfate
- C Graphite
- CAB Cellulose acetate butyrate
- DBP Butyl phthalate
- DEGDN Diethyleneglycol dinitrate
- DNT Dinotrotoluene
- DPA Diphenylamine
- EC Ethyl centralite
- H2O Water
- HZTZ Bisdihydrazinotetrazine
- KS Potassium sulfate
- MGO Magnesium oxide
- NCxx.yy Nitrocellulose with a nitration percentage of xx.yy%
- NDPA 2-nitrodiphenylamine
- NG Glyceryl trinitrate
- NQ Nitroguanidine
- PB2CO4 Basic lead oxide
- RDX Cyclo-1,3,5-trimethylene-2,4,6-trinitramine

3.4 Thermodynamic Properties. The U.S. Army Research, Development, and Engineering Center (ARDEC) Report "Interior Ballistics Firing Data Library of Closed Breech, Single Combustion Chamber Tank Guns, Artillery Guns and Howitzers Cannon," by author Frank J. Virginia, Jr. [20], is a valuable source of existing military propellant data including many measured burning rates. All data are taken from testing of individual propellant lots. A second reference is the chapter "Thermodynamic Properties of Military Gun Propellants" written by E. Freedman in the book *Gun Propulsion Technology* [16], from which many of the ingredient listings in Table 1 have been taken. The data in this reference pertain to generic compositions rather than the variations found in individual lots of propellant.

Table 2 contains thermodynamic values required to model the remaining propellants. As shown, there is a wide range of isochoric flame temperatures (from lowest at 2,555 K to highest at 3,410 K). Estimated temperature within the gun chamber will affect modeling of product gas expansion due to the (simplified) nonideal equation of state $p(V-b)=RT$ [21], where T is a direct factor in the pressure calculation; in turn, the force of pressure on the base of the projectile will govern acceleration through $F=ma$. Propellant burning rates will also be a major factor; rates in this study were gained either from the aforementioned Virginia reference or from other sources as noted in Almeyda [18] and Cramer [19]. The propellant property labeled as Force in Table 2 is a measure of the energy contained in a unit weight of material.

Table 2. Thermodynamic Properties of Propellants

Propellant	Density (g/cm^3)	Gamma	Temperature (K)	Covolume (cm^3/g)	Force (J/g)
M10	1.669	1.2342	3,000	1.0025	1013.3
M26E1	1.611	1.2384	3,132	1.0383	1085.0
M30A1	1.683	1.2375	3,036	1.0524	1073.4
M31E1	1.642	1.2580	2,574	1.1048	973.8
JA2	1.661	1.2255	3,410	0.9978	1130.2
BAMO	1.639	1.2738	2,863	1.2218	1191.3
HELP-42	1.600	1.2780	2,555	1.22	1063.0
EX-99	1.660	1.2900	3,019	1.122	1159.0

If there were no published or experimental thermodynamic values, computer programs are available to calculate estimates. CHEETAH, BLAKE, and TRAN72 have all been used for this purpose. As an example, the formulation for M1 (extracted from the Freedman chapter, and shown in Table 3) has been used for an input to the BLAKE program. The output is reproduced in Appendix A; the thermodynamic values are listed in Table 4, along with comparable data from the Virginia report. The fluctuation of values is not unexpected because any particular lot of M1 may vary slightly from the composition of the generic propellant—manufacturing methods are not so precise as to guarantee final composition in a production lot of propellant to within a fraction of a percent.

Table 3. Ingredients and Their Relative Percentages for M1 Propellant

Ingredient	BLAKE Abbreviation	Percentage
Nitrocellulose (13.15% Nitration)	NC1315	83.11
Dinitrotoluene	DNT	9.77
Butyl Phthalate	DBP	4.89
Diphenylamine	DPA	0.98
Water	H2O	0.50
Ethanol	ALC	0.75

Table 4. M1 Thermodynamic Data Calculated by BLAKE and From Virginia Reference

Source	Lot Number	Gamma	Temperature (K)	Covolume (cm^3/g)	Force (J/g)
Blake	(Generic)	1.2675	2,447	1.105	919.2
Virginia	JAN-P-309	1.2593	2,417	1.1044	911.7

Part of the calculation of thermodynamic parameters includes estimation of final combustion gases and their relative amounts. A section of Appendix A titled "Constituent Concentrations" shows gases (and possible solid or liquid products) expected to be created by each mole of burned energetic material. If relatively large amounts of toxic or corrosive products are noted, the propellant could be dropped from further analysis or else flagged for special consideration later in the study.

The computation of burning rate parameters is not yet so straightforward as is the case with thermodynamic values, since there is no computer program to calculate rates from chemical composition. Obviously the best source is through experimental data from closed-bomb analysis of the actual propellant [22–24]. Estimates of burning rates and propellant densities could be taken from a member of the "family" of propellants if the formulation of the unknown material is similar (within a percentage point or two) to the major ingredients of a known propellant, but the user should be aware that it is only an estimate and needs to be proven through experimental means.

3.5 Estimate of Available Energy. IBHVG2 computations were used to evaluate the potential energy of each propellant in the gun system model. An assumption made for this step was that there would be a constant charge weight for the various energetic materials. Since most fielded granular charges have maximum loading densities (amount of propellant mass per unit chamber volume) in the range of 0.80 g/cm^3 to 0.90 g/cm^3, a suitable value for this study was chosen at 0.85 g/cm^3 so that the interior ballistics program now has all the necessary parameters to proceed with a constant-pressure calculation. The purpose of this step is to quickly determine whether the charge could meet the minimum requirement of projectile exit velocity while keeping chamber pressure no higher than the user-defined maximum. The program artificially ties breech pressure to a given value (by converting the necessary amount of propellant to gas at each time step) until the charge is completely burned; then the gases are allowed to continue expanding (and accelerating the projectile) until maximum travel is accomplished. This process approximates what would be the perfect combination of propellant surface area and burning rate in order to transfer maximum energy to the projectile. CONPRESS does not require estimates for either grain geometry or burning rate; IBHVG2 requires either burning rate or grain geometry, although this is just a formality—both can be made to vary in order to complete the calculation.

Computed projectile exit velocities using IBHVG2 are listed in Table 5 for each of the remaining candidate propellants. The user-required velocity is 848 m/s; each velocity in the table is compared to that value via a percentage of minimum requirement. All considered

Table 5. Constant-Pressure Calculations of Exit Velocity

Propellant	Exit Velocity (m/s)	Comparison (%)
M10	867	102.2
M26E1	858	101.2
M30A1	886	104.5
M31E1	825	97.3
JA2	902	106.4
BAMO	914	107.8
HELP-42	879	103.7
EX-99	894	105.4

propellants except M31E1 attained over 100% of minimum and will be passed on to the next step in the study.

A sample output from the constant-pressure computation for M26E1 is included as Appendix B of this report.

3.6 Propellant Grain Geometry. A parametric feature allows IBHVG2 to vary propellant grain dimensions in order to calculate how each geometry will perform in the modeled gun system. By adjusting one grain measurement (in this case the web, or burn-through distance between grain perforations and between the outer grain surface and closest perforations) the program can compute entire ballistic cycles for a series of grain sizes and can find the maximum pressure and the expected projectile exit velocity for each situation. Appendix C is the printout from the performance calculations for M30A1; it includes a table of input and output values for each set of dimensions. A short summary of that information is shown in Table 6, where the computed maximum pressure is closest to 448 MPa at a web size of 3.06 mm for the grain with 19 perforations; for the 7-perf grain the targeted pressure is reached at a web size of 3.38 mm; the single-perf simulations show maximum pressure of 448 MPa at the web thickness of 4.72 mm. Projectile exit velocities are 861 m/s, 856 m/s, and 812 m/s, respectively, showing that the multiperforated grains transferred more energy to the projectile than did the mono-perforated grain. Both the 19-perf and 7-perf solutions exceeded minimum required projectile velocity,

while the single did not. Other grain dimension sizes (length 18.3 mm and perforation diameter 0.457 mm) were held constant during the parametric variations of web—this means the computed grain diameter of the 19-perf solution is

$$3.06 * 6 + 0.457 * 5 = 20.6 \text{ mm},$$

which would make the grain length slightly shorter than its width. By increasing the perforation diameter, the grain could be longer (perforation length is restricted by the ability of combustion gases to escape confinement, dependent on diameter and expected burning rates of the propellant)—but this is an exercise best left to expert ballisticians. For current purposes, it is enough to realize that the multiperforated M30A1 grains can satisfy system requirements.

Table 6 also contains information about pressure felt on the projectile base at the time of muzzle exit. The "Z@Exit" column is an estimate of the mass fraction burned at projectile exit. The last column is an estimated length of projectile travel when computed charge burnout occurs. In the bottom two rows of single-perf data, the charge is not expected to burn completely by the time the projectile exits the gun muzzle; this could be a clue to the possibility of unacceptable secondary muzzle blast and flash should the charge consist of this grain geometry.

For the 19-perf granular solution in Table 6, projectile travel is only slightly more than 2/3 maximum allowable—suggesting that there is yet more flexibility in charge manipulation in order to get even higher exit velocities within user limitations. For example, with a slightly larger loading density (assuming more propellant can be loaded into the chamber) and a larger grain web in order to keep down the maximum pressure for the increased charge, the results are as in Table 7. As charge mass increases from 12.50 kg to 13.50 kg, the web size is increased from 3.0168 mm to 3.3527 mm in order to keep maximum pressure at the 448-MPa limitation. (Increased grain web size results in a lower surface-to-mass ratio; thus the pressure peak can be maintained even though the greater charge mass transfers more energy to the projectile—assuming all the propellant still burns out within the gun tube.) Loading densities for the different charge weights are printed in the second column. Values in the right-most column,

Table 6. **Computed M30A1 Simulations With Different Grain Geometries and Web Sizes**

No. of Perforations	Web (mm)	Maximum Pressure (MPa)	Exit Velocity (m/s)	Exit Pressure (MPa)	Z@Exit	X@Burnout (m)
19	3.00	470.129	868.56	84.350	1.000	3.940
	3.02	463.022	866.16	84.667	1.000	4.274
	3.04	456.125	863.60	84.946	1.000	4.218
	3.06	449.431	860.93	85.206	1.000	4.553
	3.08	442.933	858.40	85.503	1.000	4.495
	3.10	436.620	855.71	85.764	1.000	4.832
	3.12	430.488	853.11	86.053	1.000	4.773
	3.14	424.527	850.57	86.356	1.000	5.111
	3.16	418.731	847.84	86.613	1.000	5.051
	3.18	413.094	845.20	86.902	1.000	5.390
	3.20	407.608	842.51	87.181	1.000	5.328
7	3.30	458.389	860.98	85.192	1.000	4.700
	3.32	453.193	858.73	85.494	1.000	5.050
	3.34	448.116	856.24	85.729	1.000	4.999
	3.36	443.157	853.78	85.979	1.000	5.351
	3.38	438.312	851.36	86.244	1.000	5.298
	3.40	433.576	848.90	86.498	1.000	5.651
	3.42	428.946	846.55	86.795	1.000	5.598
	3.44	424.419	844.01	87.033	1.000	5.952
	3.46	419.990	841.55	87.301	1.000	5.897
	3.48	415.657	839.03	87.555	1.000	6.252
	3.50	411.418	836.59	87.840	1.000	6.609
1	4.60	464.580	824.68	89.090	1.000	5.530
	4.62	461.798	822.66	89.303	1.000	5.498
	4.64	459.051	820.62	89.473	1.000	5.860
	4.66	456.340	818.59	89.694	1.000	5.828
	4.68	453.663	816.55	89.949	1.000	6.192
	4.70	451.018	814.50	90.133	1.000	6.158
	4.72	448.406	812.44	90.351	1.000	6.125
	4.74	445.826	810.37	90.607	1.000	6.490
	4.76	443.278	808.29	90.788	1.000	6.456
	4.78	440.759	806.21	90.854	0.999	6.840
	4.80	438.270	804.13	90.480	0.995	6.840

Table 7. M30A1 Charge Weight Variations for 19-Perf Granulation

Charge Weight (kg)	Loading Density (g/cm^3)	Web (mm)	Maximum Pressure (MPa)	Exit Velocity (m/s)	Z	Trav @ B.O. (m)
12.50	0.838	3.017	448	857.1	1.0	4.410
12.75	0.855	3.097	448	862.4	1.0	4.473
13.00	0.872	3.179	448	867.3	1.0	5.144
13.25	0.888	3.264	448	871.6	1.0	5.561
13.50	0.905	3.353	448	875.2	1.0	6.070

projectile travel at the point of charge burnout, grow larger as the charge weight and web size increase—since there is no change in maximum pressure it requires a longer burning cycle to completely consume the charge. The IBHVG2 computation for this study is in Appendix D.

For direct comparison of the different propellants, the major analysis kept a constant loading density of approximately 0.85 g/cm^3 for the gun simulation. The results are summarized in Table 8—each propellant is listed with the three grain types, their corresponding web sizes for 448 MPa maximum pressure, and the calculated projectile exit velocity in each situation. Propellant types with a superscript "a" after the name included at least one granulation satisfying the minimum user requirements. M30A1, JA2, and EX-99 each met the velocity goal with one or more multiperf granulations, while BAMO was the only propellant type to qualify with all the grain types. The rest of the formulations, although they all had potential for 848 m/s as shown in the constant-pressure calculations, could not reach that level when simulated as a standard charge consisting of single-, 7-, or 19-perf grains. BAMO exhibited the highest computed velocity in both constant-pressure and granular configurations; JA2 was the next-best computed velocity in both simulations.

Unlike the majority of propellants listed in Table 8, EX-99 shows higher computed velocities for the 7-perf grain type than for the 19-perf. This is because of "two-tiered" burning rate data and their effect in the gun model. Many IB programs (including IBHVG2) represent the

Table 8. Summary of Gun System Study Performance Calculations

Propellant	Grain Geometry		
	19-Perf	7-Perf	1-Perf
M10	844 m/s (2.56 mm)	841 m/s (2.76 mm)	807 m/s (3.82 mm)
M26E1	836 m/s (3.48 mm)	835 m/s (3.76 mm)	806 m/s (5.20 mm)
M30A1[a]	861 m/s (3.06 mm)	856 m/s (3.34 mm)	812 m/s (4.72 mm)
JA2[a]	875 m/s (4.42 mm)	867 m/s (4.91 mm)	812 m/s (7.20 mm)
BAMO[a]	881 m/s (3.13 mm)	877 m/s (3.47 mm)	859 m/s (5.06 mm)
HELP-42	807 m/s (0.883 mm)	813 m/s (0.980 mm)	836 m/s (1.375 mm)
EX-99[a]	845 m/s (2.29 mm)	858 m/s (2.52 mm)	845 m/s (3.57 mm)

[a] Included at least one granulation satisfying the minimum user requirements.

propellant burning rate equation in the form $R=aP^n$, where P is the instantaneous pressure, n is its exponent, and a is the coefficient used to calculate R as the rate of linear regression of the propellant surface. Usually the values of a and n do not change for the entire range of pressures encountered during the IB calculation, as is the case for the first five propellants in Table 8 (although each propellant has its own unique values for a and n). The EX-99 data were supplied with experimental burning rate values—three different pressures (P_1, P_2, P_3) and a corresponding rate (r_1, r_2, r_3) for each. IBHVG2 used these values to create an aP^n representation between the first two pressures, and again between the last two pressures. The solution values for a and n were not the same over the two pressure regions for EX-99. In effect, the IB code used values a_I and n_I for pressures between P_1 and P_2 (and for all pressure levels below P_1), and values a_j and n_j for pressures between P_2 and P_3 (and for all pressure levels above P_3). The "two-tier" rates can produce effects such as the higher exit velocity for the 7-perf EX-99 charge than for its counterpart 19- and single-perf granular charges when the breakpoint (P_2) is in the range of pressures experienced during the IB cycle.

The exponent n for HELP-42 was much higher than that of the other propellants; its effect on the model was to produce the highest projectile exit velocity for the single-perf Help-42 propellant and the lowest velocity for its corresponding 19-perf charge. This result is an interaction with the projectile/bore resistance profile and the timing of gas production by the burning granular surface.

3.7 Propellant Zoning. Although there was no requirement for a lower-velocity charge in this study, a calculation of lighter charge weights for the JA2 19-perf grain solution gave the information in Table 9. The "Charge Burned" column shows the fraction of main charge consumed at the time of projectile exit—none of the charge weights smaller than 11.0 kg burned out. If a low-zone artillery application had been a requirement with velocity at or below 760 m/s, then this propellant granulation (web of 4.43 mm and no changes in either length or perforation diameter) would not meet specifications unless incomplete charge burnout was acceptable to the user.

3.8 Propellant Suitability. The final step in the first round of propellant performance testing could be as simple as listing data such as that in Table 8 and providing it to the original requesting authority. In this study, BAMO appears to be the most suitable propellant, since it gives the highest muzzle energy and has the flexibility of using any of the three granulations. M30A1 and JA2 both provided solutions with the multiperforated grain types but fell short with the single-perf geometry. More likely, there will be additional constraints put on final selection, such as the following:

- Propellants will be ranked according to highest calculated velocities within a particular grain geometry;

- Environmental and economic costs due to manufacturing or demilitarization will determine rankings;

- Additional performance details, such as computed chamber combustion temperatures, will be factored in with velocities to produce a ranking scheme;

Table 9. Charge Zoning Applications With 19-Perf JA2 Propellant

Charge Weight (kg)	Maximum Pressure (MPa)	Exit Velocity (m/s)	Charge Burned (Fraction)	X@Brnout (m)
8.000	136.723	552.40	0.951	6.840
8.200	144.193	566.44	0.957	6.840
8.400	152.005	580.44	0.962	6.840
8.600	160.176	594.40	0.967	6.840
8.800	168.724	608.33	0.972	6.840
9.000	177.670	622.23	0.976	6.840
9.200	187.032	636.11	0.980	6.840
9.400	196.837	649.97	0.984	6.840
9.600	207.107	663.78	0.988	6.840
9.800	217.869	677.62	0.991	6.840
10.00	229.151	691.42	0.993	6.840
10.20	240.985	705.19	0.995	6.840
10.40	253.402	718.98	0.997	6.840
10.60	266.441	732.71	0.998	6.840
10.80	280.142	746.48	0.999	6.840
11.00	294.547	760.18	0.999	6.840
11.20	309.701	773.96	1.000	6.820
11.40	325.660	787.63	1.000	6.840
11.60	342.479	801.36	1.000	6.545
11.80	360.222	815.23	1.000	6.187
12.00	378.957	828.91	1.000	5.973
12.20	398.759	842.70	1.000	5.664
12.40	419.717	856.61	1.000	5.422
12.60	441.926	870.48	1.000	5.167
12.80	465.492	884.45	1.000	4.982
13.00	490.528	898.46	1.000	4.702

- Further testing, such as supplemental calculations with other projectile weights or secondary propelling charges, will be indicated;

- Temperature variations should be considered if the propellant is to be used in climatic extremes of desert, tropical, or polar regions;

- If no candidate propellants survive the process, the requester may ask for variations in ingredient ratios in order to find a viable charge;

- Follow-on calculations with one-, two-, or higher-dimensional IB programs may be indicated so that pressure waves or other secondary interior ballistic effects might be discovered [12, 13].

The comment concerning the choice of IB code should be addressed before this report could be considered complete. IBHVG2 was used because of its automatic input-varying feature. Most of the currently available one- or multi-dimensional IB programs lack the ability to automatically vary any of the input parameters. In order to complete several of the process steps (finding web size versus grain geometry, computing various charge weights and noting amount burned at time of projectile exit, etc.), the number of individual IB cycles to be calculated can be very large. The labor required to modify input data, compute each situation, tabulate output values, and analyze the results could be extremely large if each calculation is done separately. Therefore, the use of a code with an automated parametric function is crucial, especially during the initial phase of propellant screening. The same type of reasoning can lead to tremendous savings in time and labor in virtually all steps of the propellant developmental process where automated models can be fitted with parameter variation [25].

3.9 Next Step. Other "tools" in the propellant production and testing flow diagram will need the information from a performance analysis, whether the results are used for re-formulation of a new propellant or for additional filtering of existing choices. Before the user elects an energetic material, he will require more data about manufacturing costs, vulnerability, shelf life, environmental compatibility, and a host of other factors dealing with propellants. The initial performance comparisons are a small but important part of the overall formulation and selection process.

4. Lessons Learned and Tools Needed

The example test case is a simplistic exercise: no variations of gun hardware were considered; no propellant reformulation was envisioned; no multidimensional IB analysis was performed. Yet it is clear that some functions are necessary and others are nonexistent. To be complete, the model-based performance process still requires software tools to estimate density and burning rates of virtual propellants—semi-empirical and first-principle burning rate models are currently under development at the Army Research Laboratory [26], and models exist to predict crystal densities within a subset of crystalline space groups [27]. Automated search methods for IB solutions are absolutely necessary for minimization of the labor involved in computation and analysis. As the overall propellant creation and testing methods become formalized, there will certainly be other areas where software tools need to be developed or utilized for individual and composite steps in the sequence—estimation of processing costs, toxicity hazards, mechanical properties, disposal and demilitarization requirements, and many other activities.

Along with the computer programs is a critical need for databases to be assembled with the parameters required for software tools. With enough data, the missing tools for estimation of propellant density and burning rates might be created; vulnerability, compatibility, temperature sensitivity, and a dozen other empirical methods could follow. At the least, such gathered data would make the tasks of modelers much easier and faster.

Clear and complete performance and environmental requirements might shorten the performance modeling too. A standardized questionnaire could alert the modeler to additional factors in zoning, temperature maximums, projectile acceleration limits, and other stipulations not apparent during construction of an initial set of performance requirements. Ideally, a database of existing environmental regulations and constraints should be incorporated into the process to flag the user about possible problems with manufacture, movement, and disposal of energetic materials.

5. Summary

We have demonstrated the preliminary steps in a new formulation process for gun propellants that can minimize life-cycle costs by science-based design. The earliest steps in this process use modeling and simulation of the properties, processing, and performance of the candidate in order to screen potential candidates, eliminate probable poor performers, and identify candidates that show promise. In this exercise, user requirements of maximum pressure limitation and minimum muzzle energy for a Navy 5-inch 54-caliber gun were presented. The most promising candidate(s) to meet the user requirement from a set of 10 existing formulations representing single-, double- and triple-based propellants, as well as other novel energetic mixtures, was determined. Since not all performance and properties models exist, it was necessary to use limited empirical information to perform parts of the exercise. Down-selection of the propellants proceeded first through consideration of ingredient toxicity, then calculation of thermodynamic properties, estimation of theoretical maximum energy, determination of actual granular solutions, and listing of additional final considerations. At the end of the exercise, 4 of the 10 original formulations survived the simulation, and information is available at this point for a user to rank the suitability of the propellant according to his requirements.

The number of steps in a complete screening analysis would seemingly be endless, just as the infinite amount of propellant variations to be considered might appear when first contemplated. But the list of available propellant formulations is small when compared to current computer capabilities, and a performance testing sequence with defined steps and parametric searching methods can quickly determine which propellants can meet user requirements without extensive firing range exercises. When compared to cost of experimental tests of the same materials, the amount of resources saved by model-based filtering is enormous.

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Appendix A:

BLAKE Calculations for Generic M1 Propellant

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*************  BLAKE Thermodynamic Equilibrium & Gun Code  *****************
*          ARLware < Director, WMRD/ARL, APG, MD  21005-5066               *
*                   Attn : A. Kotlar, AMSRL-WM-BD >                         *
****************************************************************************

                     ***  BLAKE   Version 221.50  ***

      Tyger! Tyger! Burning bright/ In the forests of the night.
      What immortal hand or eye/ Dare frame thy fearful symmetry?
                                        ---William Blake  (1757-1827)

   16:07:20                                                 6-APR-1999

> TITLE, GENERIC M1

> COM,NC1315,83.11,DNT,9.77,DBP,4.89,DPA,0.98,H2O,0.50,ALC,0.75

  ******************************************************************
  <<<          The binary library being used is based on          >>>
  <<<               SBLAKLYB.LIB dated 11 August 1998             >>>
  <<<                                                             >>>
  <<<       This binary library was created on 24-SEP-1998        >>>
  ******************************************************************


   16:07:20                                 6-APR-1999  Page  1.

                              GENERIC M1

                           THE COMPOSITION IS

 Name     Pct Wt    Pct Mole    Delta H (J/mol)          FORMULA


NC1315    83.110      .244      -6.8890E+08     C    H    O     N
                                                6000 7364 10271  2636

  DNT      9.770    44.210      -6.5900E+04     C    H    O     N
                                                   7    6    4     2
```

DBP	4.890	14.480	-8.4260E+05	$C_{16} H_{22} O_{4}$
DPA	.980	4.773	1.1190E+05	$C_{12} N_{1} H_{11}$
H2O	.500	22.875	-2.8583E+05	$H_{2} O_{1}$
ALC	.750	13.418	-2.7710E+05	$C_{2} H_{6} O_{1}$

The Elements and their Atom Percentages

C	25.597
H	31.357
O	34.025
N	9.022

Formula Weight = 1009.775

The Heat of Formation is -2340.7 J/g = -2.364E+06 J/mol
= -559.46 cal/g = -5.649E+05 cal/mol

```
> GUN,0.05,0.05,0.4
```

CONSTITUENT CONCENTRATIONS - MOLES PER KGM OF COMPOUND

NAME		1)	2)	3)	4)
CO	GAS	2.29775E+01	2.29841E+01	2.29721E+01	2.29376E+01
H2	GAS	9.50757E+00	9.44288E+00	9.35897E+00	9.24995E+00
H2O	GAS	5.98865E+00	6.02345E+00	6.05732E+00	6.09215E+00
N2	GAS	4.46041E+00	4.45214E+00	4.44157E+00	4.42848E+00
CO2	GAS	2.36138E+00	2.33947E+00	2.32619E+00	2.32276E+00
H	GAS	1.69823E-02	1.12191E-02	8.56769E-03	6.96643E-03
OH	GAS	2.06596E-03	1.36908E-03	1.05132E-03	8.63253E-04
NH3	GAS	8.10015E-03	1.81443E-02	3.03683E-02	4.49315E-02
HCN	GAS	4.77970E-03	1.10574E-02	1.91618E-02	2.94333E-02
CH4	GAS	1.62997E-03	7.66132E-03	2.01363E-02	4.13460E-02
O	GAS	2.48982E-06	1.13317E-06	6.92114E-07	4.82439E-07
O2	GAS	6.37302E-07	2.90323E-07	1.77820E-07	1.24651E-07
NO	GAS	9.00247E-05	6.15728E-05	4.88600E-05	4.15520E-05
CHO	GAS	6.85851E-04	1.03823E-03	1.36422E-03	1.69659E-03
CH2O	GAS	1.45379E-03	3.21654E-03	5.33672E-03	7.86246E-03

HNCO	GAS	4.06787E-04	9.26268E-04	1.58314E-03	2.40638E-03
NH2	GAS	4.64501E-05	6.85664E-05	8.76048E-05	1.05662E-04
CH3	GAS	7.31242E-05	2.39203E-04	5.06736E-04	8.95092E-04
NH	GAS	6.03941E-07	6.11197E-07	6.19887E-07	6.33044E-07
C2H2	GAS	1.25930E-05	6.41052E-05	1.83132E-04	4.10910E-04
HNO	GAS	3.97127E-07	4.00910E-07	4.06277E-07	4.15525E-07
HO2	GAS	1.21678E-08	8.17384E-09	6.38757E-09	5.38038E-09
C2H4	GAS	1.04761E-06	1.10999E-05	4.93235E-05	1.52020E-04
N	GAS	1.00572E-07	6.93893E-08	5.55090E-08	4.75971E-08
CN	GAS	5.84721E-07	9.18693E-07	1.25311E-06	1.61986E-06
N2O	GAS	3.61315E-08	3.74717E-08	3.90376E-08	4.10817E-08
NCO	GAS	2.73096E-07	4.28349E-07	5.84300E-07	7.57305E-07
HNO2	GAS	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
CH2	GAS	2.55410E-07	5.74641E-07	9.69875E-07	1.45750E-06
C	GAS	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
NO2	GAS	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
FORMAC	GAS	5.42035E-04	1.19880E-03	1.99208E-03	2.94845E-03
C(S)	SOLID	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00

TOTAL GAS (MOLES/KG)	45.3324	45.2984	45.2466	45.1710

CONSTITUENT CONCENTRATIONS - MOLES PER KGM OF COMPOUND

NAME		5)	6)	7)	8)
CO	GAS	2.28777E+01	2.27878E+01	2.26665E+01	2.25136E+01
H2	GAS	9.11047E+00	8.93571E+00	8.72471E+00	8.47960E+00
H2O	GAS	6.12997E+00	6.17114E+00	6.21603E+00	6.26414E+00
N2	GAS	4.41323E+00	4.39517E+00	4.37445E+00	4.35116E+00
CO2	GAS	2.33074E+00	2.35106E+00	2.38457E+00	2.43146E+00
H	GAS	5.88089E-03	5.09719E-03	4.50813E-03	4.05113E-03
OH	GAS	7.40195E-04	6.56138E-04	5.97905E-04	5.57619E-04
NH3	GAS	6.18910E-02	8.11497E-02	1.02486E-01	1.25583E-01
HCN	GAS	4.21954E-02	5.77090E-02	7.61666E-02	9.76892E-02
CH4	GAS	7.34602E-02	1.17984E-01	1.75340E-01	2.44728E-01
O	GAS	3.65674E-07	2.95264E-07	2.51069E-07	2.22888E-07
O2	GAS	9.53861E-08	7.81214E-08	6.77253E-08	6.16155E-08
NO	GAS	3.70115E-05	3.42002E-05	3.26063E-05	3.19280E-05
CHO	GAS	2.05200E-03	2.44228E-03	2.87740E-03	3.36568E-03
CH2O	GAS	1.08379E-02	1.42960E-02	1.82605E-02	2.27449E-02
HNCO	GAS	3.42923E-03	4.68750E-03	6.22034E-03	8.06945E-03
NH2	GAS	1.23644E-04	1.42049E-04	1.61195E-04	1.81242E-04

CH3	GAS	1.42466E-03	2.11222E-03	2.96843E-03	3.99649E-03
NH	GAS	6.52591E-07	6.79944E-07	7.16152E-07	7.61697E-07
C2H2	GAS	8.02648E-04	1.42623E-03	2.35908E-03	3.68390E-03
HNO	GAS	4.30369E-07	4.52266E-07	4.82529E-07	5.22183E-07
HO2	GAS	4.78366E-09	4.45251E-09	4.31702E-09	4.33842E-09
C2H4	GAS	3.79141E-04	8.17489E-04	1.57827E-03	2.78883E-03
N	GAS	4.27529E-08	3.98361E-08	3.82821E-08	3.77544E-08
CN	GAS	2.03988E-06	2.53223E-06	3.11645E-06	3.81221E-06
N2O	GAS	4.38331E-08	4.75197E-08	5.23836E-08	5.86637E-08
NCO	GAS	9.59587E-07	1.20374E-06	1.50417E-06	1.87724E-06
HNO2	GAS	0.00000E+00	0.00000E+00	1.80811E-09	2.04088E-09
CH2	GAS	2.05655E-06	2.78752E-06	3.67181E-06	4.73006E-06
C	GAS	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
NO2	GAS	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
FORMAC	GAS	4.10009E-03	5.48343E-03	7.14035E-03	9.11716E-03
C(S)	SOLID	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL GAS (MOLES/KG)		45.0694	44.9350	44.7670	44.5666

* * SUMMARY OF PROPELLANT THERMO PROPERTIES * *

Truncated virial equation of state with L-J 6,12 potential is being used

Rho/L g/cc	Temp K	Press MPa	Imptus J/g	Mol Wt Gas	Co-Vol cc/g	Frozen Gamma	Balrgy J/g	U J/g	PHI
1).05000	2436.	48.79	918.2	22.059	1.181	1.2630	3490.9	-2340.7	1.0627
2).10000	2439.	103.9	918.7	22.076	1.158	1.2639	3480.9	-2340.7	1.1310
3).15000	2443.	166.1	919.0	22.101	1.133	1.2654	3462.4	-2340.7	1.2047
4).20000	2447.	236.0	919.2	22.138	1.105	1.2675	3436.0	-2340.7	1.2838
5).25000	2454.	314.5	919.5	22.188	1.077	1.2702	3402.9	-2340.7	1.3683
6).30000	2462.	402.4	919.7	22.254	1.048	1.2734	3364.1	-2340.7	1.4583
7).35000	2471.	500.2	919.9	22.338	1.018	1.2770	3320.9	-2340.7	1.5536
8).40000	2483.	608.9	920.1	22.438	.989	1.2810	3274.3	-2340.7	1.6545

> QUIT

Run time = 1.15 seconds

Appendix B:

IBHVG2 Constant-Pressure Calculations Using M26E1 Propellant

INTENTIONALLY LEFT BLANK.

ERRTOL= 1.1920929E-07

```
1                                                                       IBHVG2.505     DATE              TIME

0 CARD    1 --> $COMM
  CARD    2 -->      GREEN GUN TEST CASE - INDIAN HEAD SYSTEM
  CARD    3 --> $GUN
  CARD    4 -->     TRAV = 6.840    CHAM = 0.01506    $ 919 CUBIC INCHES
  CARD    5 -->     GRVE = 0.12852  LAND = 0.127  TWST = 24   G/L = 1.66 $ ESTIMATES
  CARD    6 -->  $  CPTS = 6
  CARD    7 -->  $  DIST = 0.0,    0.04455, 0.14732, 0.8260, 0.8913, 1.0592
  CARD    8 -->  $  DIAM = 0.12965, 0.13655, 0.13929, 0.132588, 0.12852, 0.12852
  CARD    9 --> $PROJ
  CARD   10 -->     PRWT = 49.895
  CARD   11 --> $RESI
  CARD   12 -->     NPTS = 5
  CARD   13 -->     TRAV = 0.0, 0.00508, 0.04318, 0.1397, 7.62
  CARD   14 -->     PRES = 3.4474, 0.6894757, 0.6894757, 8.2737, 8.2737
  CARD   15 --> $INFO
  CARD   16 -->     POPT = 1,1,1,0
  CARD   17 -->     RUN = 'GREEN GUN TEST CASE - M26E1'
  CARD   18 -->  $  GRAD = 3
  CARD   19 -->     CONP = 2    PRES = 448
  CARD   20 --> $COMM PRIM
  CARD   21 -->     NAME = 'PRIMER'  CHWT = 0.12637  FORC = 146140
  CARD   22 -->     GAMA = 1.2015    COV = 0.0010838   TEMP = 3377
  CARD   23 --> $PROP
  CARD   24 -->     NAME = 'M26E1'   CHWT = 11.567   FORC = 1085031
  CARD   25 -->     GAMA = 1.2384    COV = 0.0010383  TEMP = 3132
  CARD   26 -->     FORM = '7P'
  CARD   27 -->     LEN = 0.018288  PD = 0.0004572  WEB = 0.003467  RHO = 1611
  CARD   28 -->     ALPH = 0.7468  BETA = 0.0033778
  CARD   29 --> $COMM PARA
  CARD   30 -->     VARY = 'CHWT'  DECK = 'PROP'  NTH = 1
  CARD   31 -->     FROM = 11.5  BY = 0.1  TO = 15.01
  CARD   32 --> $END
1GREEN GUN TEST CASE - M26E1                                            IBHVG2.505     DATE              TIME


 ------------
 - GUN TUBE -
 ------------

   TYPE:                                              CHAMBER VOLUME (M3):         0.01506        TRAVEL
(M):                   6.84000
   GROOVE  DIAMETER  (M):              0.12852          LAND  DIAMETER  (M):                          0.12700
GROOVE/LAND RATIO (-):          1.660
```

```
   TWIST (CALS/TURN):              24.0       BORE AREA (M2):            0.01286      HEAT-LOSS
OPTION:                 1
   SHELL THICKNESS (M):          0.000102       SHELL CP (J/KG-K):           460.3163        SHELL
DENSITY (KG/M3):    7861.0918
   INITIAL SHELL TEMP (K):         293.       AIR HO (W/M**2-K):         11.3482

 -------------
 - PROJECTILE -
 -------------

   TYPE:                                        TOTAL WEIGHT (KG):           49.895       WEIGHT
PREDICTOR OPTION:          0

 -------------
 - RESISTANCE -
 -------------

   AIR RESISTANCE OPTION:            1        WALL HEATING FRACTION:        0.000
   RESISTIVE PRESSURE MULT INDEX:    3         RESISTIVE FACTOR               1.000      FRICTION
TABLE LENGTH:             5

    I    TRAVEL (M)       PRESSURE (MPA)          I    TRAVEL (M)       PRESSURE (MPA)          I
TRAVEL (M),      PRESSURE (MPA)

    1       0.000              3.447              3       0.043              0.689              5
7.620            8.274
    2      0.005             0.689            4      0.140            8.274

 ----------
 - GENERAL -
 ----------

   MAX TIME STEP (S):            0.000100        PRINT STEP (S):              0.000000          MAX
RELATIVE ERROR (-):      0.00200
   PRINT OPTIONS:            1 1 1 0 1 1      STORE OPTION:                        0       CONSTANT-
PRESSURE OPTION:          2
   GRADIENT MODEL: LAGRANGIAN

 ---------
 - RECOIL -
 ---------

   RECOIL OPTION:                    0        TYPE:                                          RECOILING
WEIGHT (KG):           0.

 -----------------------
```

- CONSTANT-PRESSURE RUN -

MAINTAIN PRESSURE (MPA): 448. WITHIN (MPA): 0.0 BY
VARYING: PROPELLANT SURFACE AREA
1GREEN GUN TEST CASE - M26E1 IBHVG2.505 DATE TIME

- CHARGE 1 -

TYPE: M26E1 GRAINS: 1.0000 7P WEIGHT
(KG): 11.5670
EROSIVE COEFF (-): 0.000000 CHARGE IGN CODE: 0 CHARGE IGN
AT (S): 0.00000E+00

	PROPERTIES AT LAYER BOUNDARIES OF 1ST	2ND	3RD	LAT SURFACES 4TH
AT DEPTH (M):	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1611.000
GAMMA (-):	------	------	------	1.2384
FORCE (J/KG):	------	------	------	1085031.
COVOLUME (M3/KG):	------	------	------	1.0383E-03
FLAME TEMP (K):	------	------	------	3132.0
BURNING RATE EXPS:	------	------	------	0.7468
BURNING RATE COEFFS:	------	------	------	3.3778E-03

1GREEN GUN TEST CASE - M26E1 IBHVG2.505 DATE TIME

	TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1	SURFACE AREA (M**2)	BURNING RATE (M/S)
0	0.000	0.000	0.00	10469.	448.000	432.608	401.823	3132.	0.233	0.223	0.314
	0.100	0.001	10.27	10475.	448.000	432.598	401.794	3131.	0.233	0.056	0.314
BARREL RESISTANCE OVERCOME - PROJECTILE MOVING											
	0.200	0.002	20.55	10495.	448.000	432.569	401.708	3128.	0.234	0.169	0.314
	0.300	0.005	30.86	10527.	448.000	432.521	401.563	3124.	0.235	0.283	0.314
	0.400	0.008	41.19	10533.	448.000	432.513	401.538	3118.	0.237	0.402	0.314
	0.500	0.013	51.53	10533.	448.000	432.513	401.539	3110.	0.239	0.519	0.314
	0.600	0.019	61.86	10533.	448.000	432.513	401.539	3101.	0.242	0.634	0.314
	0.700	0.025	72.19	10533.	448.000	432.513	401.540	3091.	0.245	0.749	0.314
	0.800	0.033	82.52	10533.	448.000	432.514	401.540	3079.	0.249	0.864	0.314
	0.900	0.042	92.85	10533.	448.000	432.514	401.541	3066.	0.253	0.979	0.314
	1.000	0.052	103.17	10517.	448.000	432.537	401.610	3052.	0.258	1.097	0.314

1.100	0.062	113.48	10497.	448.000	432.566	401.699	3038.	0.263	1.212	0.314
1.200	0.074	123.77	10475.	448.000	432.599	401.796	3022.	0.269	1.326	0.314
1.300	0.087	134.03	10451.	448.000	432.634	401.902	3006.	0.275	1.440	0.314
1.400	0.101	144.27	10425.	448.000	432.672	402.017	2990.	0.282	1.554	0.314
1.500	0.116	154.48	10397.	448.000	432.713	402.139	2973.	0.290	1.667	0.314
1.600	0.132	164.66	10367.	448.000	432.757	402.270	2957.	0.297	1.779	0.314
1.700	0.149	174.82	10353.	448.000	432.778	402.334	2940.	0.306	1.888	0.314
1.800	0.167	184.97	10353.	448.000	432.778	402.335	2923.	0.314	1.997	0.314
1.900	0.186	195.13	10352.	448.000	432.779	402.336	2906.	0.324	2.107	0.314
2.000	0.206	205.28	10352.	448.000	432.779	402.337	2890.	0.333	2.218	0.314
2.100	0.227	215.43	10352.	448.000	432.779	402.337	2874.	0.343	2.328	0.314
2.200	0.249	225.59	10352.	448.000	432.779	402.338	2858.	0.354	2.439	0.314
2.300	0.272	235.74	10352.	448.000	432.780	402.339	2842.	0.365	2.549	0.314
2.400	0.296	245.89	10351.	448.000	432.780	402.340	2827.	0.377	2.659	0.314
2.500	0.321	256.05	10351.	448.000	432.780	402.341	2812.	0.389	2.768	0.314
2.600	0.347	266.20	10351.	448.000	432.781	402.342	2798.	0.402	2.878	0.314
2.700	0.374	276.35	10351.	448.000	432.781	402.343	2784.	0.415	2.987	0.314
2.800	0.403	286.50	10351.	448.000	432.781	402.344	2771.	0.428	3.096	0.314
2.900	0.432	296.65	10350.	448.000	432.782	402.345	2758.	0.442	3.206	0.314
3.000	0.462	306.80	10350.	448.000	432.782	402.346	2745.	0.457	3.315	0.314
3.100	0.493	316.96	10350.	448.000	432.782	402.347	2733.	0.472	3.424	0.314
3.200	0.525	327.11	10350.	448.000	432.783	402.348	2722.	0.487	3.533	0.314
3.300	0.559	337.26	10349.	448.000	432.783	402.349	2711.	0.503	3.642	0.314
3.400	0.593	347.41	10349.	448.000	432.783	402.350	2700.	0.520	3.750	0.314
3.500	0.628	357.56	10349.	448.000	432.784	402.352	2690.	0.537	3.859	0.314
3.600	0.664	367.71	10349.	448.000	432.784	402.353	2680.	0.554	3.968	0.314
3.700	0.702	377.86	10348.	448.000	432.785	402.354	2671.	0.572	4.077	0.314
3.800	0.740	388.00	10348.	448.000	432.785	402.355	2662.	0.590	4.186	0.314
3.900	0.779	398.15	10348.	448.000	432.785	402.356	2653.	0.609	4.295	0.314
4.000	0.820	408.30	10347.	448.000	432.786	402.358	2645.	0.628	4.404	0.314
4.100	0.861	418.45	10347.	448.000	432.786	402.359	2637.	0.648	4.513	0.314
4.200	0.903	428.60	10347.	448.000	432.787	402.360	2629.	0.668	4.622	0.314
4.300	0.947	438.74	10346.	448.000	432.787	402.362	2622.	0.689	4.731	0.314
4.400	0.991	448.89	10346.	448.000	432.788	402.363	2615.	0.710	4.841	0.314
4.500	1.036	459.04	10346.	448.000	432.788	402.365	2608.	0.732	4.950	0.314
4.600	1.083	469.18	10345.	448.000	432.789	402.366	2602.	0.754	5.059	0.314
4.700	1.130	479.33	10345.	448.000	432.789	402.368	2595.	0.777	5.169	0.314
4.800	1.179	489.48	10345.	448.000	432.790	402.369	2589.	0.800	5.278	0.314
4.900	1.228	499.62	10344.	448.000	432.790	402.371	2584.	0.823	5.388	0.314
5.000	1.279	509.77	10344.	448.000	432.791	402.372	2578.	0.847	5.497	0.314
5.100	1.330	519.91	10344.	448.000	432.791	402.374	2573.	0.872	5.607	0.314
5.200	1.383	530.06	10343.	448.000	432.792	402.376	2568.	0.897	5.717	0.314
5.300	1.436	540.20	10343.	448.000	432.792	402.377	2563.	0.922	5.827	0.314

1GREEN GUN TEST CASE - M26E1 IBHVG2.505 DATE TIME

TIME TRAV VEL ACC BREECH MEAN BASE MEAN FRAC SURFACE BURNING

	(MS)	(M)	(M/S)	(G)	PRESS (MPA)	PRESS (MPA)	PRESS (MPA)	TEMP (K)	BURN 1	AREA (M**2)	RATE (M/S)
0	5.400	1.491	550.34	10343.	448.000	432.793	402.379	2558.	0.948	5.937	0.314
	5.500	1.546	560.49	10342.	448.000	432.794	402.381	2554.	0.975	6.047	0.314
	5.593	1.599	569.96	10342.	448.000	432.794	402.382	2550.	1.000	0.000	0.314
PROPELLANT 1 BURNED OUT											
	5.600	1.603	570.65	10314.	446.810	431.645	401.316	2548.	1.000	0.000	0.000
	5.700	1.660	580.57	9915.	429.871	415.293	386.138	2528.	1.000	0.000	0.000
	5.800	1.719	590.10	9536.	413.800	399.779	371.738	2509.	1.000	0.000	0.000
	5.900	1.778	599.27	9176.	398.549	385.057	358.073	2490.	1.000	0.000	0.000
	6.000	1.839	608.10	8835.	384.073	371.083	345.103	2472.	1.000	0.000	0.000
	6.100	1.900	616.61	8511.	370.330	357.816	332.788	2454.	1.000	0.000	0.000
	6.200	1.962	624.80	8203.	357.277	345.215	321.093	2436.	1.000	0.000	0.000
	6.300	2.025	632.70	7911.	344.875	333.243	309.981	2419.	1.000	0.000	0.000
	6.400	2.088	640.32	7633.	333.087	321.864	299.418	2402.	1.000	0.000	0.000
	6.500	2.153	647.68	7369.	321.877	311.043	289.374	2385.	1.000	0.000	0.000
	6.600	2.218	654.78	7117.	311.212	300.748	279.819	2369.	1.000	0.000	0.000
	6.700	2.284	661.64	6878.	301.060	290.948	270.723	2354.	1.000	0.000	0.000
	6.800	2.350	668.27	6650.	291.393	281.615	262.060	2338.	1.000	0.000	0.000
	6.900	2.417	674.69	6433.	282.181	272.723	253.807	2323.	1.000	0.000	0.000
	7.000	2.485	680.89	6225.	273.398	264.245	245.938	2308.	1.000	0.000	0.000
	7.100	2.554	686.90	6028.	265.021	256.158	238.432	2294.	1.000	0.000	0.000
	7.200	2.623	692.72	5839.	257.026	248.440	231.268	2280.	1.000	0.000	0.000
	7.300	2.692	698.35	5659.	249.391	241.070	224.428	2266.	1.000	0.000	0.000
	7.400	2.762	703.82	5487.	242.096	234.028	217.892	2252.	1.000	0.000	0.000
	7.500	2.833	709.12	5323.	235.123	227.297	211.644	2239.	1.000	0.000	0.000
	7.600	2.904	714.26	5165.	228.453	220.858	205.669	2226.	1.000	0.000	0.000
	7.700	2.976	719.25	5015.	222.070	214.697	199.950	2213.	1.000	0.000	0.000
	7.800	3.048	724.10	4871.	215.959	208.797	194.474	2201.	1.000	0.000	0.000
	7.900	3.121	728.81	4733.	210.103	203.145	189.228	2189.	1.000	0.000	0.000
	8.000	3.194	733.38	4600.	204.491	197.727	184.199	2177.	1.000	0.000	0.000
	8.100	3.267	737.83	4473.	199.108	192.531	179.376	2165.	1.000	0.000	0.000
	8.200	3.341	742.16	4351.	193.943	187.545	174.749	2153.	1.000	0.000	0.000
	8.300	3.416	746.37	4234.	188.985	182.759	170.306	2142.	1.000	0.000	0.000
	8.400	3.491	750.47	4122.	184.222	178.161	166.039	2131.	1.000	0.000	0.000
	8.500	3.566	754.45	4014.	179.645	173.743	161.939	2120.	1.000	0.000	0.000
	8.600	3.641	758.34	3910.	175.245	169.495	157.996	2109.	1.000	0.000	0.000
	8.700	3.717	762.13	3810.	171.012	165.409	154.204	2099.	1.000	0.000	0.000
	8.800	3.794	765.81	3714.	166.938	161.477	150.554	2089.	1.000	0.000	0.000
	8.900	3.871	769.41	3622.	163.016	157.691	147.040	2078.	1.000	0.000	0.000
	9.000	3.948	772.92	3533.	159.237	154.043	143.655	2069.	1.000	0.000	0.000
	9.100	4.025	776.34	3447.	155.596	150.529	140.393	2059.	1.000	0.000	0.000
	9.200	4.103	779.68	3364.	152.086	147.140	137.248	2049.	1.000	0.000	0.000
	9.300	4.181	782.94	3284.	148.700	143.871	134.215	2040.	1.000	0.000	0.000
	9.400	4.260	786.12	3207.	145.432	140.717	131.287	2030.	1.000	0.000	0.000
	9.500	4.338	789.23	3132.	142.278	137.672	128.461	2021.	1.000	0.000	0.000

9.600	4.417	792.27	3060.	139.231	134.732	125.732	2012.	1.000	0.000	0.000
9.700	4.497	795.23	2991.	136.288	131.890	123.095	2003.	1.000	0.000	0.000
9.800	4.576	798.13	2924.	133.443	129.144	120.546	1995.	1.000	0.000	0.000
9.900	4.656	800.97	2859.	130.692	126.489	118.082	1986.	1.000	0.000	0.000
10.000	4.737	803.74	2796.	128.032	123.921	115.698	1978.	1.000	0.000	0.000
10.100	4.817	806.45	2735.	125.457	121.435	113.392	1969.	1.000	0.000	0.000
10.200	4.898	809.11	2676.	122.964	119.029	111.159	1961.	1.000	0.000	0.000
10.300	4.979	811.70	2619.	120.551	116.699	108.996	1953.	1.000	0.000	0.000
10.400	5.060	814.24	2564.	118.212	114.442	106.902	1945.	1.000	0.000	0.000
10.500	5.142	816.73	2511.	115.947	112.255	104.872	1937.	1.000	0.000	0.000
10.600	5.224	819.17	2459.	113.750	110.135	102.904	1930.	1.000	0.000	0.000

1GREEN GUN TEST CASE - M26E1 IBHVG2.505 DATE TIME

TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1	SURFACE AREA (M**2)	BURNING RATE (M/S)
0 10.700	5.306	821.56	2409.	111.620	108.079	100.996	1922.	1.000	0.000	0.000
10.800	5.388	823.89	2360.	109.554	106.084	99.145	1915.	1.000	0.000	0.000
10.900	5.470	826.18	2312.	107.549	104.149	97.349	1907.	1.000	0.000	0.000
11.000	5.553	828.43	2267.	105.603	102.270	95.605	1900.	1.000	0.000	0.000
11.100	5.636	830.63	2222.	103.713	100.446	93.912	1893.	1.000	0.000	0.000
11.200	5.719	832.79	2179.	101.878	98.674	92.268	1886.	1.000	0.000	0.000
11.300	5.803	834.90	2136.	100.094	96.953	90.670	1879.	1.000	0.000	0.000
11.400	5.886	836.98	2096.	98.361	95.280	89.118	1872.	1.000	0.000	0.000
11.500	5.970	839.01	2056.	96.676	93.654	87.609	1865.	1.000	0.000	0.000
11.600	6.054	841.01	2017.	95.038	92.072	86.141	1859.	1.000	0.000	0.000
11.700	6.138	842.97	1979.	93.445	90.534	84.713	1852.	1.000	0.000	0.000
11.800	6.223	844.89	1943.	91.894	89.037	83.324	1846.	1.000	0.000	0.000
11.900	6.307	846.78	1907.	90.385	87.581	81.973	1839.	1.000	0.000	0.000
12.000	6.392	848.63	1872.	88.916	86.163	80.657	1833.	1.000	0.000	0.000
12.100	6.477	850.45	1839.	87.486	84.782	79.375	1827.	1.000	0.000	0.000
12.200	6.562	852.24	1806.	86.092	83.437	78.127	1820.	1.000	0.000	0.000
12.300	6.647	854.00	1774.	84.735	82.127	76.911	1814.	1.000	0.000	0.000
12.400	6.733	855.72	1742.	83.412	80.850	75.726	1808.	1.000	0.000	0.000
12.500	6.819	857.41	1712.	82.123	79.606	74.572	1802.	1.000	0.000	0.000
12.525	6.840	857.83	1704.	81.806	79.300	74.287	1801.	1.000	0.000	0.000

PROJECTILE EXIT

1GREEN GUN TEST CASE - M26E1 IBHVG2.505 DATE TIME

CONDITIONS AT:	PMAX	MUZZLE
TIME (MS):	5.593	12.525
TRAVEL (M):	1.5988	6.8400
VELOCITY (M/S)	569.96	857.83

ACCELERATION (G):	10342.	1704.
BREECH PRESS (MPA):	447.9999	81.8058
MEAN PRESS (MPA):	432.7940	79.2997
BASE PRESS (MPA):	402.3822	74.2875
MEAN TEMP (K):	2550.	1801.
Z CHARGE 1 (-):	1.000	1.000

ENERGY BALANCE SUMMARY	JOULE	%
TOTAL CHEMICAL:	52645464.	100.00
(1) INTERNAL GAS:	30269280.	57.50
(2) WORK AND LOSSES:	22376184.	42.50
(A) PROJECTILE KINETIC:	18358272.	34.87
(B) GAS KINETIC:	1418647.	2.69
(C) PROJECTILE ROTATIONAL:	157282.	0.30
(D) FRICTIONAL WORK TO TUBE:	0.	0.00
(E) OTHER FRICTIONAL WORK:	718839.	1.37
(F) WORK DONE AGAINST AIR:	69870.	0.13
(G) HEAT CONVECTED TO BORE:	1653274.	3.14
(H) RECOIL ENERGY:	0.	0.00

LOADING DENSITY (KG/M3):	768.061
CHARGE WT/PROJECTILE WT:	0.232
PIEZOMETRIC EFFICIENCY:	0.466
EXPANSION RATIO:	6.840

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Appendix C:

IBHVG2 Performance Calculations for M30A1 Propellant

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ERRTOL= 1.1920929E-07

```
1                                                       IBHVG2.505     DATE            TIME

0 CARD   1 --> $COMM
  CARD   2 -->     GREEN GUN TEST CASE - INDIAN HEAD SYSTEM
  CARD   3 --> $GUN
  CARD   4 -->    TRAV = 6.840   CHAM = 0.01506   $ 919 CUBIC INCHES
  CARD   5 -->    GRVE = 0.12852  LAND = 0.127  TWST = 25  G/L = 1.49 $ ESTIMATES
  CARD   6 --> $PROJ
  CARD   7 -->    PRWT = 49.895
  CARD   8 --> $RESI
  CARD   9 -->    NPTS = 5
  CARD  10 -->    TRAV = 0.0,     0.00508,    0.04318,    0.1397, 7.62
  CARD  11 -->    PRES = 3.4474, 0.6894757, 0.6894757, 8.2737, 8.2737
  CARD  12 --> $INFO
  CARD  13 -->    POPT = 1,1,1,0  DELP=0.0005
  CARD  14 -->    RUN = 'GREEN GUN TEST CASE - M30A1 19P PERFORMANCE'
  CARD  15 --> $PRIM
  CARD  16 -->    NAME = 'PRIMER'  CHWT = 0.12637  FORC = 146140
  CARD  17 -->    GAMA = 1.2015    COV = 0.0010838 TEMP = 3377
  CARD  18 --> $PROP
  CARD  19 -->    NAME = 'M30A1'   CHWT = 12.65      FORC = 1073374
  CARD  20 -->    GAMA = 1.2375    COV = 0.00105239  TEMP = 3036
  CARD  21 -->    LEN = 0.018288   PD = 0.0004572    WEB = 0.003467  RHO = 1683
  CARD  22 -->    ALPH = 0.8063    BETA = 0.00196836
  CARD  23 -->    FORM = '19P'
  CARD  24 --> $PARA
  CARD  25 -->    VARY = 'WEB'   DECK = 'PROP' NTH = 1
  CARD  26 -->    FROM = 0.0030  BY = 0.00002  TO = 0.00501
  CARD  27 --> $END
1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE            IBHVG2.505     DATE            TIME
```

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------------
- GUN TUBE -
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 TYPE:                                   CHAMBER VOLUME (M3):        0.01506    TRAVEL (M):                    6.84000
 GROOVE DIAMETER (M):          0.12852   LAND DIAMETER (M):          0.12700    GROOVE/LAND RATIO (-):           1.490
 TWIST (CALS/TURN):               25.0   BORE AREA (M2):             0.01285    HEAT-LOSS OPTION:                    1
 SHELL THICKNESS (M):         0.000102   SHELL CP (J/KG-K):         460.3163    SHELL DENSITY (KG/M3):       7861.0918
 INITIAL SHELL TEMP (K):          293.   AIR HO (W/M**2-K):          11.3482

--------------
- PROJECTILE -
--------------

 TYPE:                                   TOTAL WEIGHT (KG):           49.895    WEIGHT PREDICTOR OPTION:             0

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- RESISTANCE -
--------------

 AIR RESISTANCE OPTION:             1    WALL HEATING FRACTION:        0.000
 RESISTIVE PRESSURE MULT INDEX:     3    RESISTIVE FACTOR              1.000    FRICTION TABLE LENGTH:               5

  I   TRAVEL (M)      PRESSURE (MPA)      I   TRAVEL (M)      PRESSURE (MPA)      I   TRAVEL (M),     PRESSURE (MPA)

  1      0.000            3.447           3      0.043            0.689           5      7.620            8.274
  2      0.005            0.689           4      0.140            8.274

-----------
- GENERAL -
-----------
```

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MAX TIME STEP (S):          0.000100     PRINT STEP (S):             0.000500     MAX RELATIVE ERROR (-):       0.00200
PRINT OPTIONS:            1 1 1 0 1 1    STORE OPTION:                      0     CONSTANT-PRESSURE OPTION:           0
GRADIENT MODEL: LAGRANGIAN

----------
- RECOIL -
----------

RECOIL OPTION:                    0      TYPE:                                     RECOILING WEIGHT (KG):             0.

----------
- PRIMER -
----------

TYPE: PRIMER                              GAMMA (-):                   1.2015     FORCE (J/KG):                146140.
COVOLUME (M3/KG):         1.0838E-03     FLAME TEMP (K):              3377.0     WEIGHT (KG):                 0.126370
1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE               IBHVG2.505     DATE              TIME

------------
- CHARGE 1 -
------------

TYPE: M30A1                               GRAINS:              1284.0     19P     WEIGHT (KG):                  12.6500
EROSIVE COEFF (-):          0.000000     CHARGE IGN CODE:                    0     CHARGE IGN AT (S):        0.00000E+00
GRAIN LENGTH (M):           0.018288     GRAIN DIAMETER (M):         0.020286     PERF DIAMETER (M):           0.000457
INNER WEB (M):              0.003000     MIDDLE WEB (M):             0.003000     OUTER WEB (M):               0.003000

                      PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES     PROPERTIES AT LAYER BOUNDARIES OF  END SURFACES
                          1ST        2ND        3RD        4TH               1ST        2ND        3RD          4TH

AT DEPTH (M):           ------     ------     ------     0.00000           ------     ------     ------      0.00000
```

ADJACENT LAYER WT %:	------	------	------	100.000	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03	------	------	------	1.9684E-03

PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES

	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

	TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1
0	0.000	0.000	0.00	0.	2.493	2.493	2.493	3377.	0.000
	0.277	0.000	0.00	0.	3.447	3.447	3.447	3287.	0.001
SHOT-START PRESSURE ACHIEVED									
	0.500	0.000	0.02	23.	4.448	4.410	4.334	3234.	0.001
	1.000	0.000	0.30	96.	7.515	7.360	7.049	3156.	0.003
	1.500	0.000	1.02	206.	12.078	11.743	11.075	3112.	0.005

2.000	0.001	2.41	369.	18.664	18.064	16.863	3084.	0.008
2.500	0.003	4.77	607.	27.925	26.939	24.965	3066.	0.013
3.000	0.006	8.51	929.	40.612	39.102	36.082	3052.	0.020
3.500	0.012	13.99	1323.	57.536	55.386	51.085	3040.	0.029
4.000	0.021	21.69	1838.	79.654	76.667	70.692	3027.	0.041
4.500	0.034	32.25	2493.	107.798	103.747	95.643	3011.	0.057
5.000	0.053	46.37	3282.	142.481	137.147	126.481	2992.	0.077
5.500	0.081	64.63	4189.	183.637	176.828	163.212	2967.	0.103
6.000	0.119	87.64	5208.	230.353	221.890	204.965	2937.	0.136
6.500	0.169	115.87	6340.	280.646	270.343	249.738	2901.	0.177
7.000	0.236	149.87	7519.	331.295	319.077	294.641	2859.	0.226
7.500	0.320	189.46	8611.	378.243	364.249	336.263	2813.	0.285
8.000	0.426	234.02	9527.	417.611	402.130	371.167	2764.	0.352
8.500	0.555	282.49	10200.	446.570	429.994	396.844	2714.	0.426
9.000	0.709	333.60	10602.	463.912	446.682	412.223	2664.	0.508
9.500	0.889	386.04	10744.	470.072	452.612	417.691	2617.	0.594
9.555	0.910	391.85	10746.	470.129	452.667	417.743	2612.	0.604
LOCAL PRESSURE MAX DETECTED								
10.000	1.095	438.61	10664.	466.677	449.348	414.689	2572.	0.683
10.500	1.327	490.34	10412.	455.930	439.010	405.170	2529.	0.774
11.000	1.585	540.51	10011.	438.775	422.506	389.970	2488.	0.863
11.500	1.867	587.38	9047.	397.438	382.737	353.334	2431.	0.917
12.000	2.172	629.02	7937.	349.841	336.943	311.148	2367.	0.948
12.500	2.495	665.36	6914.	305.970	294.734	272.264	2304.	0.967
13.000	2.836	697.07	6048.	268.841	259.013	239.357	2246.	0.983
13.500	3.192	724.86	5299.	236.727	228.116	210.894	2191.	0.992
14.000	3.560	749.21	4651.	208.957	201.399	186.282	2137.	0.997
14.500	3.940	770.63	4100.	185.341	178.678	165.351	2086.	0.999
14.911	4.260	786.34	3710.	168.618	162.589	150.530	2047.	1.000
PROPELLANT 1 BURNED OUT								
15.000	4.331	789.55	3632.	165.275	159.372	147.567	2038.	1.000
15.500	4.730	806.37	3237.	148.339	143.079	132.559	1994.	1.000

16.000	5.137	821.40	2902.	134.007	129.291	119.857	1953.	1.000
16.500	5.551	834.91	2617.	121.770	117.517	109.012	1915.	1.000
17.000	5.971	847.13	2371.	111.236	107.383	99.677	1879.	1.000
17.500	6.398	858.22	2158.	102.099	98.593	91.581	1846.	1.000
18.000	6.829	868.33	1971.	94.120	90.917	84.510	1815.	1.000
18.012	6.840	868.56	1967.	93.939	90.742	84.350	1814.	1.000

PROJECTILE EXIT

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

CONDITIONS AT:	PMAX	MUZZLE
TIME (MS):	9.555	18.012
TRAVEL (M):	0.9102	6.8400
VELOCITY (M/S)	391.85	868.56
ACCELERATION (G):	10746.	1967.
BREECH PRESS (MPA):	470.1292	93.9389
MEAN PRESS (MPA):	452.6669	90.7424
BASE PRESS (MPA):	417.7426	84.3496
MEAN TEMP (K):	2612.	1814.
Z CHARGE 1 (-):	0.604	1.000

ENERGY BALANCE SUMMARY	JOULE	%
TOTAL CHEMICAL:	57251044.	100.00
(1) INTERNAL GAS:	34206272.	59.75
(2) WORK AND LOSSES:	23044770.	40.25
(A) PROJECTILE KINETIC:	18820410.	32.87

(B)	GAS KINETIC:	1606417.	2.81
(C)	PROJECTILE ROTATIONAL:	148600.	0.26
(D)	FRICTIONAL WORK TO TUBE:	0.	0.00
(E)	OTHER FRICTIONAL WORK:	718397.	1.25
(F)	WORK DONE AGAINST AIR:	68561.	0.12
(G)	HEAT CONVECTED TO BORE:	1682386.	2.94
(H)	RECOIL ENERGY:	0.	0.00

LOADING DENSITY (KG/M3):	848.365
CHARGE WT/PROJECTILE WT:	0.256
PIEZOMETRIC EFFICIENCY:	0.455
EXPANSION RATIO:	6.836

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE   IBHVG2.505   DATE   TIME

PARAMETRIC VARIABLES: / 1/ PROP 1 WEB

	/1/	PMAX	VMUZ	PMUZ	Z(1)	X@Z=1
0	0.3000E-02	470.129	868.56	84.350	1.000	3.940
	0.3020E-02	463.022	866.16	84.667	1.000	4.274
	0.3040E-02	456.125	863.60	84.946	1.000	4.218
	0.3060E-02	449.431	860.93	85.206	1.000	4.553
	0.3080E-02	442.933	858.40	85.503	1.000	4.495
	0.3100E-02	436.620	855.71	85.764	1.000	4.832
	0.3120E-02	430.488	853.11	86.053	1.000	4.773
	0.3140E-02	424.527	850.57	86.356	1.000	5.111
	0.3160E-02	418.731	847.84	86.613	1.000	5.051
	0.3180E-02	413.094	845.20	86.902	1.000	5.390
	0.3200E-02	407.608	842.51	87.181	1.000	5.328

0.3220E-02	402.270	839.91	87.488	1.000	5.668
0.3240E-02	397.071	837.15	87.756	1.000	5.605
0.3260E-02	392.008	834.42	88.035	1.000	5.945
0.3280E-02	387.078	831.82	88.358	1.000	5.882
0.3300E-02	382.273	828.99	88.616	1.000	6.222
0.3320E-02	377.590	826.23	88.903	1.000	6.564
0.3340E-02	373.022	823.55	89.217	1.000	6.498
0.3360E-02	368.567	820.72	89.485	1.000	6.840
0.3380E-02	364.221	817.91	89.753	1.000	6.840
0.3400E-02	359.980	815.13	90.027	1.000	6.840
0.3420E-02	355.841	812.29	90.269	0.999	6.840
0.3440E-02	351.801	809.52	90.526	0.999	6.840
0.3460E-02	347.853	806.65	90.743	0.999	6.840
0.3480E-02	343.997	803.85	90.976	0.998	6.840
0.3500E-02	340.230	800.94	91.163	0.997	6.840
0.3520E-02	336.548	798.11	91.365	0.997	6.840
0.3540E-02	332.952	795.19	91.524	0.996	6.840
0.3560E-02	329.434	792.32	91.694	0.995	6.840
0.3580E-02	325.993	789.39	91.825	0.994	6.840
0.3600E-02	322.628	786.50	91.966	0.993	6.840
0.3620E-02	319.337	783.57	92.073	0.992	6.840
0.3640E-02	316.115	780.67	92.179	0.990	6.840
0.3660E-02	312.963	777.77	92.270	0.989	6.840
0.3680E-02	309.876	774.81	92.310	0.987	6.840
0.3700E-02	306.854	771.89	92.333	0.985	6.840
0.3720E-02	303.894	768.98	92.344	0.983	6.840
0.3740E-02	300.995	766.03	92.325	0.981	6.840
0.3760E-02	298.155	763.11	92.323	0.979	6.840
0.3780E-02	295.373	760.18	92.308	0.977	6.840
0.3800E-02	292.646	757.26	92.302	0.975	6.840
0.3820E-02	289.972	754.31	92.271	0.973	6.840
0.3840E-02	287.351	751.38	92.244	0.971	6.840

0.3860E-02	284.782	748.46	92.221	0.969	6.840
0.3880E-02	282.262	745.53	92.186	0.967	6.840
0.3900E-02	279.791	742.59	92.150	0.964	6.840
0.3920E-02	277.367	739.67	92.112	0.962	6.840
0.3940E-02	274.987	736.74	92.070	0.960	6.840
0.3960E-02	272.653	733.81	92.024	0.958	6.840
0.3980E-02	270.361	730.88	91.971	0.955	6.840
0.4000E-02	268.112	727.95	91.910	0.953	6.840
0.4020E-02	265.904	725.03	91.829	0.951	6.840
0.4040E-02	263.736	722.10	91.730	0.948	6.840
0.4060E-02	261.607	719.17	91.613	0.945	6.840

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE   IBHVG2.505   DATE   TIME

PARAMETRIC VARIABLES: / 1/ PROP 1 WEB

/1/	PMAX	VMUZ	PMUZ	Z(1)	X@Z=1
0 0.4080E-02	259.515	716.26	91.482	0.943	6.840
0.4100E-02	257.460	713.34	91.329	0.940	6.840
0.4120E-02	255.442	710.43	91.158	0.937	6.840
0.4140E-02	253.458	707.54	90.983	0.934	6.840
0.4160E-02	251.509	704.64	90.767	0.930	6.840
0.4180E-02	249.595	701.75	90.542	0.927	6.840
0.4200E-02	247.712	698.87	90.290	0.923	6.840
0.4220E-02	245.860	696.00	90.032	0.920	6.840
0.4240E-02	244.041	693.14	89.740	0.916	6.840
0.4260E-02	242.251	690.30	89.431	0.912	6.840
0.4280E-02	240.491	687.47	89.104	0.908	6.840
0.4300E-02	238.760	684.65	88.749	0.903	6.840
0.4320E-02	237.057	681.84	88.377	0.899	6.840
0.4340E-02	235.381	679.05	87.970	0.895	6.840
0.4360E-02	233.733	676.28	87.542	0.890	6.840
0.4380E-02	232.111	673.53	87.077	0.885	6.840

0.4400E-02	230.514	670.80	86.580	0.880	6.840
0.4420E-02	228.943	668.10	86.041	0.874	6.840
0.4440E-02	227.396	665.42	85.413	0.868	6.840
0.4460E-02	225.874	662.77	84.725	0.862	6.840
0.4480E-02	224.375	660.15	84.047	0.855	6.840
0.4500E-02	222.898	657.56	83.379	0.849	6.840
0.4520E-02	221.444	655.00	82.722	0.843	6.840
0.4540E-02	220.012	652.47	82.075	0.837	6.840
0.4560E-02	218.601	649.97	81.438	0.831	6.840
0.4580E-02	217.212	647.50	80.811	0.825	6.840
0.4600E-02	215.844	645.06	80.194	0.819	6.840
0.4620E-02	214.497	642.64	79.586	0.814	6.840
0.4640E-02	213.168	640.26	78.987	0.808	6.840
0.4660E-02	211.858	637.89	78.397	0.802	6.840
0.4680E-02	210.568	635.56	77.816	0.797	6.840
0.4700E-02	209.296	633.25	77.244	0.792	6.840
0.4720E-02	208.042	630.97	76.680	0.786	6.840
0.4740E-02	206.806	628.71	76.124	0.781	6.840
0.4760E-02	205.587	626.48	75.577	0.776	6.840
0.4780E-02	204.386	624.27	75.038	0.771	6.840
0.4800E-02	203.201	622.08	74.506	0.766	6.840
0.4820E-02	202.033	619.92	73.982	0.761	6.840
0.4840E-02	200.880	617.78	73.465	0.756	6.840
0.4860E-02	199.744	615.67	72.956	0.751	6.840
0.4880E-02	198.622	613.57	72.454	0.746	6.840
0.4900E-02	197.516	611.50	71.959	0.742	6.840
0.4920E-02	196.426	609.45	71.471	0.737	6.840
0.4940E-02	195.349	607.43	70.990	0.732	6.840
0.4960E-02	194.287	605.42	70.516	0.728	6.840
0.4980E-02	193.238	603.43	70.048	0.723	6.840
0.5000E-02	192.204	601.47	69.586	0.719	6.840

```
0 CARD  28 --> $SAVE
  CARD  29 --> $INFO
  CARD  30 -->    POPT = 1,0,0,0  $ PRINT INPUT ECHO, MINIMIZE TRAJ PRINT
  CARD  31 -->    RUN = 'GREEN GUN TEST CASE - M30A1 7P PERFORMANCE'
  CARD  32 --> $PROP
  CARD  33 -->    FORM = '7P'
  CARD  34 --> $END
1GREEN GUN TEST CASE - M30A1 7P PERFORMANCE              IBHVG2.505     DATE          TIME


 ------------
 - GUN TUBE -
 ------------

  TYPE:                                 CHAMBER VOLUME (M3):        0.01506    TRAVEL (M):                 6.84000
  GROOVE DIAMETER (M):       0.12852    LAND DIAMETER (M):          0.12700    GROOVE/LAND RATIO (-):        1.490
  TWIST (CALS/TURN):            25.0    BORE AREA (M2):             0.01285    HEAT-LOSS OPTION:                 1
  SHELL THICKNESS (M):      0.000102    SHELL CP (J/KG-K):         460.3163    SHELL DENSITY (KG/M3):    7861.0918
  INITIAL SHELL TEMP (K):       293.    AIR H0 (W/M**2-K):          11.3482

 --------------
 - PROJECTILE -
 --------------

  TYPE:                                 TOTAL WEIGHT (KG):           49.895    WEIGHT PREDICTOR OPTION:          0

 --------------
 - RESISTANCE -
 --------------

  AIR RESISTANCE OPTION:           1    WALL HEATING FRACTION:        0.000
  RESISTIVE PRESSURE MULT INDEX:   3    RESISTIVE FACTOR              1.000    FRICTION TABLE LENGTH:            5
```

```
  I   TRAVEL (M)      PRESSURE (MPA)        I   TRAVEL (M)      PRESSURE (MPA)        I   TRAVEL (M),     PRESSURE (MPA)

  1       0.000             3.447           3       0.043             0.689           5       7.620             8.274
  2       0.005             0.689           4       0.140             8.274

 -----------
 - GENERAL -
 -----------

  MAX TIME STEP (S):          0.000100      PRINT STEP (S):               0.000500      MAX RELATIVE ERROR (-):     0.00200
  PRINT OPTIONS:           1 0 0 0 1 1      STORE OPTION:                        0      CONSTANT-PRESSURE OPTION:         0
  GRADIENT MODEL: LAGRANGIAN

 ----------
 - RECOIL -
 ----------

  RECOIL OPTION:                      0     TYPE:                                       RECOILING WEIGHT (KG):           0.

 ----------
 - PRIMER -
 ----------

  TYPE: PRIMER                              GAMMA (-):                      1.2015      FORCE (J/KG):               146140.
  COVOLUME (M3/KG):        1.0838E-03       FLAME TEMP (K):                 3377.0      WEIGHT (KG):               0.126370
1GREEN GUN TEST CASE - M30A1 7P PERFORMANCE                 IBHVG2.505      DATE              TIME

 ------------
 - CHARGE 1 -
 ------------
```

```
TYPE: M30A1                            GRAINS:          2950.9    7P    WEIGHT (KG):               12.6500
EROSIVE COEFF (-):       0.000000      CHARGE IGN CODE:                0    CHARGE IGN AT (S):    0.00000E+00
GRAIN LENGTH (M):        0.018288      GRAIN DIAMETER (M):      0.013372    PERF DIAMETER (M):       0.000457
INNER WEB (M):           0.003000      OUTER WEB (M):           0.003000
```

	PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES				PROPERTIES AT LAYER BOUNDARIES OF END SURFACES			
	1ST	2ND	3RD	4TH	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03	------	------	------	1.9684E-03

	PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES			
	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03

```
1GREEN GUN TEST CASE - M30A1 7P PERFORMANCE          IBHVG2.505     DATE            TIME
```

PARAMETRIC VARIABLES: / 1/ PROP 1 WEB

	/1/	PMAX	VMUZ	PMUZ	Z(1)	X@Z=1
0	0.3000E-02	554.378	895.63	81.329	1.000	3.058
	0.3020E-02	546.707	893.39	81.584	1.000	3.396
	0.3040E-02	539.250	891.14	81.839	1.000	3.351
	0.3060E-02	532.000	888.88	82.094	1.000	3.694
	0.3080E-02	524.946	886.62	82.351	1.000	3.648
	0.3100E-02	518.081	884.36	82.611	1.000	3.603
	0.3120E-02	511.396	882.10	82.876	1.000	3.947
	0.3140E-02	504.889	879.91	83.161	1.000	3.900
	0.3160E-02	498.548	877.63	83.426	1.000	3.854
	0.3180E-02	492.369	875.24	83.667	1.000	4.199
	0.3200E-02	486.349	872.86	83.912	1.000	4.151
	0.3220E-02	480.477	870.48	84.160	1.000	4.499
	0.3240E-02	474.750	868.12	84.418	1.000	4.450
	0.3260E-02	469.163	865.78	84.684	1.000	4.800
	0.3280E-02	463.710	863.37	84.931	1.000	4.750
	0.3300E-02	458.389	860.98	85.192	1.000	4.700
	0.3320E-02	453.193	858.73	85.494	1.000	5.050
	0.3340E-02	448.116	856.24	85.729	1.000	4.999
	0.3360E-02	443.157	853.78	85.979	1.000	5.351
	0.3380E-02	438.312	851.36	86.244	1.000	5.298
	0.3400E-02	433.576	848.90	86.498	1.000	5.651
	0.3420E-02	428.946	846.55	86.795	1.000	5.598
	0.3440E-02	424.419	844.01	87.033	1.000	5.952
	0.3460E-02	419.990	841.55	87.301	1.000	5.897
	0.3480E-02	415.657	839.03	87.555	1.000	6.252
	0.3500E-02	411.418	836.59	87.840	1.000	6.609
	0.3520E-02	407.270	834.04	88.091	1.000	6.552
	0.3540E-02	403.209	831.50	88.349	1.000	6.840
	0.3560E-02	399.234	829.03	88.625	1.000	6.840

0.3580E-02	395.338	826.44	88.850	1.000	6.840
0.3600E-02	391.522	823.87	89.079	0.999	6.840
0.3620E-02	387.785	821.34	89.315	0.999	6.840
0.3640E-02	384.123	818.75	89.524	0.999	6.840
0.3660E-02	380.534	816.22	89.750	0.999	6.840
0.3680E-02	377.016	813.57	89.922	0.998	6.840
0.3700E-02	373.566	810.97	90.108	0.997	6.840
0.3720E-02	370.183	808.36	90.283	0.997	6.840
0.3740E-02	366.865	805.74	90.448	0.996	6.840
0.3760E-02	363.610	803.11	90.607	0.995	6.840
0.3780E-02	360.416	800.48	90.756	0.994	6.840
0.3800E-02	357.282	797.85	90.895	0.993	6.840
0.3820E-02	354.207	795.23	91.042	0.993	6.840
0.3840E-02	351.188	792.55	91.144	0.991	6.840
0.3860E-02	348.225	789.90	91.258	0.990	6.840
0.3880E-02	345.315	787.23	91.351	0.989	6.840
0.3900E-02	342.457	784.57	91.449	0.988	6.840
0.3920E-02	339.651	781.90	91.535	0.987	6.840
0.3940E-02	336.894	779.22	91.597	0.985	6.840
0.3960E-02	334.185	776.54	91.667	0.984	6.840
0.3980E-02	331.522	773.86	91.719	0.982	6.840
0.4000E-02	328.905	771.19	91.775	0.981	6.840
0.4020E-02	326.335	768.48	91.794	0.979	6.840
0.4040E-02	323.807	765.80	91.823	0.978	6.840
0.4060E-02	321.322	763.11	91.836	0.976	6.840

PARAMETRIC VARIABLES: / 1/ PROP 1 WEB

/1/	PMAX	VMUZ	PMUZ	Z(1)	X@Z=1
0 0.4080E-02	318.879	760.41	91.835	0.974	6.840
0.4100E-02	316.477	757.73	91.820	0.972	6.840

0.4120E-02	314.113	755.04	91.788	0.970	6.840
0.4140E-02	311.787	752.35	91.739	0.968	6.840
0.4160E-02	309.500	749.65	91.658	0.965	6.840
0.4180E-02	307.249	746.96	91.570	0.963	6.840
0.4200E-02	305.035	744.28	91.465	0.961	6.840
0.4220E-02	302.857	741.60	91.345	0.958	6.840
0.4240E-02	300.713	738.93	91.214	0.955	6.840
0.4260E-02	298.602	736.26	91.052	0.952	6.840
0.4280E-02	296.523	733.60	90.872	0.949	6.840
0.4300E-02	294.477	730.94	90.674	0.946	6.840
0.4320E-02	292.462	728.30	90.462	0.943	6.840
0.4340E-02	290.478	725.66	90.223	0.940	6.840
0.4360E-02	288.523	723.03	89.971	0.936	6.840
0.4380E-02	286.599	720.41	89.696	0.932	6.840
0.4400E-02	284.703	717.81	89.397	0.929	6.840
0.4420E-02	282.833	715.22	89.070	0.925	6.840
0.4440E-02	280.993	712.64	88.725	0.921	6.840
0.4460E-02	279.179	710.08	88.346	0.916	6.840
0.4480E-02	277.392	707.54	87.939	0.912	6.840
0.4500E-02	275.630	705.01	87.484	0.907	6.840
0.4520E-02	273.893	702.51	86.977	0.902	6.840
0.4540E-02	272.182	700.03	86.379	0.896	6.840
0.4560E-02	270.494	697.58	85.786	0.890	6.840
0.4580E-02	268.829	695.15	85.202	0.885	6.840
0.4600E-02	267.188	692.75	84.626	0.879	6.840
0.4620E-02	265.571	690.38	84.058	0.874	6.840
0.4640E-02	263.975	688.03	83.498	0.868	6.840
0.4660E-02	262.401	685.70	82.945	0.863	6.840
0.4680E-02	260.849	683.40	82.401	0.858	6.840
0.4700E-02	259.319	681.13	81.863	0.852	6.840
0.4720E-02	257.808	678.88	81.333	0.847	6.840
0.4740E-02	256.317	676.65	80.810	0.842	6.840

```
 0.4760E-02 254.846  674.44  80.294 0.837  6.840
 0.4780E-02 253.394  672.26  79.785 0.832  6.840
 0.4800E-02 251.962  670.10  79.283 0.828  6.840
 0.4820E-02 250.548  667.95  78.787 0.823  6.840
 0.4840E-02 249.153  665.84  78.298 0.818  6.840
 0.4860E-02 247.776  663.74  77.815 0.813  6.840
 0.4880E-02 246.416  661.66  77.339 0.809  6.840
 0.4900E-02 245.074  659.61  76.869 0.804  6.840
 0.4920E-02 243.748  657.57  76.405 0.800  6.840
 0.4940E-02 242.439  655.55  75.946 0.795  6.840
 0.4960E-02 241.147  653.56  75.494 0.791  6.840
 0.4980E-02 239.870  651.58  75.047 0.786  6.840
 0.5000E-02 238.610  649.62  74.606 0.782  6.840
1GREEN GUN TEST CASE - M30A1 7P PERFORMANCE               IBHVG2.505     DATE              TIME

0 CARD  35 --> $SAVE
  CARD  36 --> $INFO
  CARD  37 -->     RUN = 'GREEN GUN TEST CASE - M30A1 1P PERFORMANCE'
  CARD  38 --> $PROP
  CARD  39 -->     FORM = '1P'
  CARD  40 --> $END
1GREEN GUN TEST CASE - M30A1 1P PERFORMANCE               IBHVG2.505     DATE              TIME


 ------------
 - GUN TUBE -
 ------------

  TYPE:                                  CHAMBER VOLUME (M3):       0.01506    TRAVEL (M):                  6.84000
  GROOVE DIAMETER (M):         0.12852   LAND DIAMETER (M):         0.12700    GROOVE/LAND RATIO (-):         1.490
  TWIST (CALS/TURN):              25.0   BORE AREA (M2):            0.01285    HEAT-LOSS OPTION:                  1
  SHELL THICKNESS (M):        0.000102   SHELL CP (J/KG-K):        460.3163    SHELL DENSITY (KG/M3):     7861.0918
```

INITIAL SHELL TEMP (K):	293.	AIR HO (W/M**2-K):	11.3482		

- PROJECTILE -

TYPE:		TOTAL WEIGHT (KG):	49.895	WEIGHT PREDICTOR OPTION:	0

- RESISTANCE -

AIR RESISTANCE OPTION:	1	WALL HEATING FRACTION:	0.000		
RESISTIVE PRESSURE MULT INDEX:	3	RESISTIVE FACTOR	1.000	FRICTION TABLE LENGTH:	5

I	TRAVEL (M)	PRESSURE (MPA)	I	TRAVEL (M)	PRESSURE (MPA)	I	TRAVEL (M),	PRESSURE (MPA)
1	0.000	3.447	3	0.043	0.689	5	7.620	8.274
2	0.005	0.689	4	0.140	8.274			

- GENERAL -

MAX TIME STEP (S):	0.000100	PRINT STEP (S):	0.000500	MAX RELATIVE ERROR (-):	0.00200
PRINT OPTIONS:	1 0 0 0 1 1	STORE OPTION:	0	CONSTANT-PRESSURE OPTION:	0

GRADIENT MODEL: LAGRANGIAN

- RECOIL -

```
RECOIL OPTION:              0      TYPE:                              RECOILING WEIGHT (KG):          0.

----------
- PRIMER -
----------

TYPE: PRIMER                       GAMMA (-):                1.2015   FORCE (J/KG):              146140.
COVOLUME (M3/KG):     1.0838E-03   FLAME TEMP (K):           3377.0   WEIGHT (KG):              0.126370
1GREEN GUN TEST CASE - M30A1 1P PERFORMANCE          IBHVG2.505       DATE         TIME

------------
- CHARGE 1 -
------------

TYPE: M30A1                        GRAINS:            12614.     1P   WEIGHT (KG):               12.6500
 EROSIVE COEFF (-):      0.000000   CHARGE IGN CODE:                0   CHARGE IGN AT (S):      0.00000E+00
 GRAIN LENGTH (M):       0.018288   GRAIN DIAMETER (M):      0.006457   PERF DIAMETER (M):         0.000457
INNER WEB (M):          0.003000   WEB RATIO:                1.0000
```

	PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES				PROPERTIES AT LAYER BOUNDARIES OF END SURFACES			
	1ST	2ND	3RD	4TH	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03	------	------	------	1.9684E-03

PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES

	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03

1GREEN GUN TEST CASE - M30A1 1P PERFORMANCE IBHVG2.505 DATE TIME

PARAMETRIC VARIABLES: / 1/ PROP 1 WEB

	/1/	PMAX	VMUZ	PMUZ	Z(1)	X@Z=1
0	0.3000E-02	913.691	963.31	73.056	1.000	0.968
	0.3020E-02	902.632	962.34	73.348	1.000	0.952
	0.3040E-02	891.834	961.39	73.647	1.000	0.936
	0.3060E-02	881.294	958.71	73.605	1.000	0.921
	0.3080E-02	871.006	958.31	74.021	1.000	0.906
	0.3100E-02	860.959	956.54	74.163	1.000	1.185
	0.3120E-02	851.144	954.00	74.140	1.000	1.166
	0.3140E-02	841.554	952.85	74.411	1.000	1.149
	0.3160E-02	832.178	951.66	74.678	1.000	1.131
	0.3180E-02	823.008	950.43	74.940	1.000	1.114
	0.3200E-02	814.042	947.96	74.924	1.000	1.098
	0.3220E-02	805.271	946.70	75.182	1.000	1.082
	0.3240E-02	796.690	945.40	75.435	1.000	1.370
	0.3260E-02	788.293	944.07	75.684	1.000	1.352

0.3280E-02	780.073	941.68	75.676	1.000	1.333
0.3300E-02	772.026	940.32	75.922	1.000	1.315
0.3320E-02	764.144	938.94	76.164	1.000	1.297
0.3340E-02	756.422	937.52	76.402	1.000	1.279
0.3360E-02	748.858	936.08	76.637	1.000	1.579
0.3380E-02	741.445	933.76	76.637	1.000	1.559
0.3400E-02	734.181	932.30	76.869	1.000	1.539
0.3420E-02	727.061	930.82	77.098	1.000	1.520
0.3440E-02	720.082	929.32	77.324	1.000	1.501
0.3460E-02	713.234	928.06	77.626	1.000	1.482
0.3480E-02	706.517	926.25	77.766	1.000	1.789
0.3500E-02	699.929	924.77	78.011	1.000	1.769
0.3520E-02	693.466	923.12	78.204	1.000	1.748
0.3540E-02	687.122	921.46	78.397	1.000	1.728
0.3560E-02	680.896	919.28	78.421	1.000	1.708
0.3580E-02	674.784	917.67	78.631	1.000	1.689
0.3600E-02	668.782	916.04	78.839	1.000	2.002
0.3620E-02	662.887	914.40	79.044	1.000	1.980
0.3640E-02	657.099	912.75	79.247	1.000	1.959
0.3660E-02	651.413	911.08	79.449	1.000	1.938
0.3680E-02	645.825	909.40	79.647	1.000	1.918
0.3700E-02	640.335	907.71	79.845	1.000	2.238
0.3720E-02	634.941	906.00	80.040	1.000	2.216
0.3740E-02	629.640	904.29	80.233	1.000	2.193
0.3760E-02	624.426	902.56	80.425	1.000	2.172
0.3780E-02	619.299	900.83	80.615	1.000	2.150
0.3800E-02	614.259	899.08	80.804	1.000	2.476
0.3820E-02	609.305	897.33	80.991	1.000	2.452
0.3840E-02	604.431	895.91	81.330	1.000	2.429
0.3860E-02	599.637	894.12	81.509	1.000	2.407
0.3880E-02	594.920	892.41	81.727	1.000	2.739
0.3900E-02	590.279	890.52	81.869	1.000	2.714

0.3920E-02	585.709	888.87	82.124	1.000	2.690
0.3940E-02	581.214	886.90	82.224	1.000	2.667
0.3960E-02	576.789	885.08	82.401	1.000	2.644
0.3980E-02	572.433	883.53	82.722	1.000	2.978
0.4000E-02	568.144	881.66	82.880	1.000	2.954
0.4020E-02	563.921	879.81	83.052	1.000	2.929
0.4040E-02	559.763	877.96	83.223	1.000	2.905
0.4060E-02	555.668	876.31	83.524	1.000	3.244

1GREEN GUN TEST CASE - M30A1 1P PERFORMANCE IBHVG2.505 DATE TIME

PARAMETRIC VARIABLES: / 1/ PROP 1 WEB

/1/	PMAX	VMUZ	PMUZ	Z(1)	X@Z=1
0 0.4080E-02	551.633	874.42	83.683	1.000	3.218
0.4100E-02	547.658	872.67	83.927	1.000	3.193
0.4120E-02	543.742	870.66	84.017	1.000	3.168
0.4140E-02	539.883	868.99	84.331	1.000	3.511
0.4160E-02	536.081	867.14	84.534	1.000	3.484
0.4180E-02	532.335	865.29	84.737	1.000	3.458
0.4200E-02	528.642	863.37	84.893	1.000	3.805
0.4220E-02	525.004	861.45	85.055	1.000	3.778
0.4240E-02	521.417	859.65	85.318	1.000	3.750
0.4260E-02	517.880	857.81	85.552	1.000	3.724
0.4280E-02	514.392	855.89	85.735	1.000	4.073
0.4300E-02	510.953	853.95	85.894	1.000	4.045
0.4320E-02	507.562	852.10	86.146	1.000	4.017
0.4340E-02	504.217	850.14	86.302	1.000	4.369
0.4360E-02	500.917	848.29	86.579	1.000	4.340
0.4380E-02	497.663	846.29	86.705	1.000	4.312
0.4400E-02	494.453	844.39	86.949	1.000	4.667
0.4420E-02	491.285	842.49	87.199	1.000	4.637
0.4440E-02	488.159	840.54	87.407	1.000	4.608

0.4460E-02	485.075	838.59	87.615	1.000	4.965
0.4480E-02	482.032	836.62	87.813	1.000	4.934
0.4500E-02	479.028	834.65	88.033	1.000	4.904
0.4520E-02	476.063	832.67	88.244	1.000	5.263
0.4540E-02	473.136	830.69	88.454	1.000	5.232
0.4560E-02	470.248	828.69	88.665	1.000	5.201
0.4580E-02	467.396	826.66	88.803	1.000	5.562
0.4600E-02	464.580	824.68	89.090	1.000	5.530
0.4620E-02	461.798	822.66	89.303	1.000	5.498
0.4640E-02	459.051	820.62	89.473	1.000	5.860
0.4660E-02	456.340	818.59	89.694	1.000	5.828
0.4680E-02	453.663	816.55	89.949	1.000	6.192
0.4700E-02	451.018	814.50	90.133	1.000	6.158
0.4720E-02	448.406	812.44	90.351	1.000	6.125
0.4740E-02	445.826	810.37	90.607	1.000	6.490
0.4760E-02	443.278	808.29	90.788	1.000	6.456
0.4780E-02	440.759	806.21	90.854	0.999	6.840
0.4800E-02	438.270	804.13	90.480	0.995	6.840
0.4820E-02	435.810	802.07	90.110	0.990	6.840
0.4840E-02	433.380	800.03	89.743	0.986	6.840
0.4860E-02	430.978	798.00	89.380	0.982	6.840
0.4880E-02	428.605	795.99	89.020	0.978	6.840
0.4900E-02	426.258	794.00	88.662	0.975	6.840
0.4920E-02	423.940	792.02	88.308	0.971	6.840
0.4940E-02	421.649	790.05	87.957	0.967	6.840
0.4960E-02	419.384	788.11	87.608	0.963	6.840
0.4980E-02	417.144	786.17	87.263	0.959	6.840
0.5000E-02	414.930	784.25	86.921	0.955	6.840

INTENTIONALLY LEFT BLANK.

Appendix D:

Performance Calculations Varying Charge Mass of M30A1 Propellant

INTENTIONALLY LEFT BLANK.

```
ERRTOL= 1.1920929E-07
1                                          IBHVG2.505     DATE          TIME

0 CARD   1 --> $COMM
  CARD   2 -->     GREEN GUN TEST CASE - INDIAN HEAD SYSTEM
  CARD   3 --> $GUN
  CARD   4 -->    TRAV = 6.840   CHAM = 0.01506    $ 919 CUBIC INCHES
  CARD   5 -->    GRVE = 0.12852  LAND = 0.127  TWST = 25  G/L = 1.49 $ ESTIMATES
  CARD   6 -->  $  CPTS = 6
  CARD   7 -->  $  DIST = 0.0,   0.04455, 0.14732, 0.8260, 0.8913, 1.0592
  CARD   8 -->  $  DIAM = 0.12965, 0.13655, 0.13929, 0.132588, 0.12852, 0.12852
  CARD   9 --> $PROJ
  CARD  10 -->    PRWT = 49.895
  CARD  11 --> $RESI
  CARD  12 -->    NPTS = 5
  CARD  13 -->    TRAV = 0.0, 0.00508, 0.04318, 0.1397, 7.62
  CARD  14 -->    PRES = 3.4474, 0.6894757, 0.6894757, 8.2737, 8.2737
  CARD  15 --> $INFO
  CARD  16 -->    POPT = 1,1,1,0,2
  CARD  17 -->    RUN = 'GREEN GUN TEST CASE - M30A1 19P PERFORMANCE'
  CARD  18 -->  $  GRAD = 3
  CARD  19 -->  $  CONP = 2   PRES = 448  TOL = 0.1
  CARD  20 --> $PDIS
  CARD  21 -->    SHOW = 'CHWT'  DECK = 'PROP'  NTH = 1  REMK ='CHWT (KG)'
  CARD  22 --> $PDIS
  CARD  23 -->    SHOW = 'LDEN'  DECK = 'OUT'  REMK = 'L/D (G/CC)'  MULT = 0.001
  CARD  24 --> $PDIS
  CARD  25 -->    SHOW = 'WEB'  DECK = 'PROP'  NTH = 1  REMK ='WEB(MM)'  MULT = 1000.
  CARD  26 --> $PDIS
  CARD  27 -->    SHOW = 'PMAX'  DECK = 'OUT'  REMK = 'PMAX (MPA)'
  CARD  28 --> $PDIS
  CARD  29 -->    SHOW = 'VMUZ'  DECK = 'OUT'  REMK = 'VMUZ (M/S)'
```

```
CARD  30 --> $PDIS
CARD  31 -->    SHOW = 'ZMUZ(1)'  DECK = 'OUT'  REMK = 'Z @ EXIT'
CARD  32 --> $PDIS
CARD  33 -->    SHOW = 'X@BO(1)'  DECK = 'OUT'  REMK = 'X @ B.O.'
CARD  34 --> $PRIM
CARD  35 -->    NAME = 'PRIMER'  CHWT = 0.12637  FORC = 146140
CARD  36 -->    GAMA = 1.2015   COV = 0.0010838   TEMP = 3377
CARD  37 --> $PROP
CARD  38 -->    NAME = 'M30A1'   CHWT = 12.65   FORC = 1073374
CARD  39 -->    GAMA = 1.2375   COV = 0.00105239  TEMP = 3036
CARD  40 -->    LEN = 0.018288  PD = 0.0004572  WEB = 0.003467  RHO = 1683
CARD  41 -->    ALPH = 0.8063  BETA = 0.00196836
CARD  42 -->    FORM = '19P'
CARD  43 --> $PMAX
CARD  44 -->    VARY = 'WEB'  NTH = 1  TRY1 = 0.003  TRY2 = 0.0031  PMAX = 448.
CARD  45 --> $PARA
CARD  46 -->    VARY = 'CHWT'  DECK = 'PROP'  NTH = 1
CARD  47 -->    FROM = 12.5  BY = 0.25  TO = 13.6
CARD  48 --> $END
1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE            IBHVG2.505    DATE            TIME


------------
- GUN TUBE -
------------

TYPE:                                    CHAMBER VOLUME (M3):      0.01506    TRAVEL (M):                  6.84000
GROOVE DIAMETER (M):         0.12852     LAND DIAMETER (M):        0.12700    GROOVE/LAND RATIO (-):         1.490
TWIST (CALS/TURN):              25.0     BORE AREA (M2):           0.01285    HEAT-LOSS OPTION:                  1
SHELL THICKNESS (M):        0.000102     SHELL CP (J/KG-K):       460.3163    SHELL DENSITY (KG/M3):     7861.0918
INITIAL SHELL TEMP (K):         293.     AIR HO (W/M**2-K):        11.3482
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- PROJECTILE -
--------------

 TYPE:                                       TOTAL WEIGHT (KG):          49.895      WEIGHT PREDICTOR OPTION:          0

--------------
- RESISTANCE -
--------------

 AIR RESISTANCE OPTION:              1       WALL HEATING FRACTION:        0.000
 RESISTIVE PRESSURE MULT INDEX:      3       RESISTIVE FACTOR              1.000      FRICTION TABLE LENGTH:            5

  I   TRAVEL (M)       PRESSURE (MPA)         I   TRAVEL (M)      PRESSURE (MPA)        I   TRAVEL (M),      PRESSURE (MPA)

  1      0.000            3.447               3      0.043           0.689              5      7.620            8.274
  2      0.005            0.689               4      0.140           8.274

-----------
- GENERAL -
-----------

 MAX TIME STEP (S):          0.000100        PRINT STEP (S):            0.000000      MAX RELATIVE ERROR (-):     0.00200
 PRINT OPTIONS:           1 1 1 0 2 1        STORE OPTION:                     0      CONSTANT-PRESSURE OPTION:         0
 GRADIENT MODEL: LAGRANGIAN

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- RECOIL -
----------

 RECOIL OPTION:                      0       TYPE:                                    RECOILING WEIGHT (KG):           0.
```

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 - PRIMER -
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  TYPE: PRIMER                         GAMMA (-):                1.2015     FORCE (J/KG):           146140.
  COVOLUME (M3/KG):      1.0838E-03    FLAME TEMP (K):           3377.0     WEIGHT (KG):           0.126370
1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE           IBHVG2.505      DATE          TIME

 ------------
 - CHARGE 1 -
 ------------

  TYPE: M30A1                          GRAINS:            1256.2    19P     WEIGHT (KG):            12.5000
  EROSIVE COEFF (-):      0.000000     CHARGE IGN CODE:                0    CHARGE IGN AT (S):  0.00000E+00
  GRAIN LENGTH (M):       0.018288     GRAIN DIAMETER (M):      0.020387    PERF DIAMETER (M):     0.000457
  INNER WEB (M):          0.003017     MIDDLE WEB (M):          0.003017    OUTER WEB (M):         0.003017
```

	PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES				PROPERTIES AT LAYER BOUNDARIES OF END SURFACES			
	1ST	2ND	3RD	4TH	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03	------	------	------	1.9684E-03

PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES

	1ST	2ND	3RD	4TH
AT DEPTH (M):	------	------	------	0.00000
ADJACENT LAYER WT %:	------	------	------	100.000
DENSITY (KG/M3):	------	------	------	1683.000
GAMMA (-):	------	------	------	1.2375
FORCE (J/KG):	------	------	------	1073374.
COVOLUME (M3/KG):	------	------	------	1.0524E-03
FLAME TEMP (K):	------	------	------	3036.0
BURNING RATE EXPS:	------	------	------	0.8063
BURNING RATE COEFFS:	------	------	------	1.9684E-03

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1
0 0.000	0.000	0.00	0.	2.464	2.464	2.464	3377.	0.000
0.100	0.000	0.00	0.	2.768	2.768	2.768	3342.	0.000
0.200	0.000	0.00	0.	3.102	3.102	3.102	3311.	0.000
0.295	0.000	0.00	0.	3.448	3.448	3.448	3284.	0.001
SHOT-START PRESSURE ACHIEVED								
0.300	0.000	0.00	0.	3.467	3.466	3.464	3283.	0.001
0.400	0.000	0.01	10.	3.880	3.863	3.831	3259.	0.001
0.500	0.000	0.02	21.	4.330	4.297	4.231	3237.	0.001
0.600	0.000	0.05	32.	4.820	4.768	4.665	3218.	0.001
0.700	0.000	0.08	45.	5.352	5.280	5.137	3201.	0.002
0.800	0.000	0.13	58.	5.929	5.836	5.649	3185.	0.002
0.900	0.000	0.20	73.	6.555	6.438	6.204	3172.	0.002
1.000	0.000	0.28	89.	7.233	7.090	6.804	3159.	0.003
1.100	0.000	0.37	107.	7.965	7.794	7.452	3148.	0.003
1.200	0.000	0.49	125.	8.755	8.554	8.151	3139.	0.003
1.300	0.000	0.62	146.	9.608	9.373	8.904	3130.	0.004

1.400	0.000	0.77	168.	10.526	10.256	9.715	3122.	0.004
1.500	0.000	0.95	192.	11.514	11.205	10.587	3114.	0.005
1.600	0.000	1.15	219.	12.575	12.224	11.523	3108.	0.005
1.700	0.001	1.38	247.	13.715	13.319	12.527	3102.	0.006
1.800	0.001	1.64	277.	14.937	14.492	13.602	3096.	0.007
1.900	0.001	1.92	310.	16.247	15.749	14.754	3091.	0.007
2.000	0.001	2.24	345.	17.648	17.094	15.985	3086.	0.008
2.100	0.001	2.60	383.	19.147	18.531	17.301	3082.	0.009
2.200	0.002	3.00	424.	20.747	20.066	18.705	3078.	0.010
2.300	0.002	3.43	468.	22.456	21.704	20.202	3075.	0.011
2.400	0.002	3.92	515.	24.277	23.450	21.796	3071.	0.012
2.500	0.003	4.45	565.	26.218	25.310	23.493	3068.	0.013
2.600	0.003	5.03	620.	28.283	27.288	25.298	3065.	0.014
2.700	0.004	5.66	678.	30.479	29.391	27.214	3062.	0.015
2.800	0.004	6.36	740.	32.812	31.624	29.249	3059.	0.016
2.900	0.005	7.11	806.	35.288	33.994	31.406	3057.	0.018
3.000	0.006	7.93	867.	37.899	36.506	33.720	3054.	0.019
3.100	0.007	8.82	932.	40.663	39.167	36.174	3051.	0.020
3.200	0.008	9.76	1000.	43.589	41.983	38.771	3049.	0.022
3.300	0.009	10.78	1072.	46.681	44.959	41.516	3047.	0.024
3.400	0.010	11.87	1148.	49.948	48.104	44.416	3044.	0.025
3.500	0.011	13.03	1229.	53.395	51.422	47.476	3042.	0.027
3.600	0.012	14.28	1313.	57.029	54.920	50.702	3039.	0.029
3.700	0.014	15.61	1403.	60.857	58.605	54.100	3037.	0.031
3.800	0.015	17.03	1496.	64.885	62.482	57.676	3034.	0.034
3.900	0.017	18.55	1595.	69.120	66.558	61.435	3032.	0.036
4.000	0.019	20.16	1699.	73.566	70.838	65.382	3029.	0.039
4.100	0.021	21.88	1807.	78.230	75.327	69.522	3026.	0.041
4.200	0.024	23.71	1921.	83.117	80.032	73.860	3023.	0.044
4.300	0.026	25.65	2041.	88.233	84.955	78.401	3020.	0.047
4.400	0.029	27.71	2165.	93.580	90.103	83.148	3017.	0.050
4.500	0.032	29.90	2295.	99.164	95.478	88.105	3014.	0.053

4.600	0.035	32.21	2431.	104.987	101.083	93.274	3011.	0.057
4.700	0.038	34.67	2572.	111.052	106.920	98.658	3007.	0.060
4.800	0.042	37.26	2719.	117.359	112.992	104.257	3004.	0.064
4.900	0.045	40.00	2868.	123.904	119.298	110.086	3000.	0.068
5.000	0.050	42.89	3018.	130.685	125.838	116.143	2996.	0.072
5.100	0.054	45.92	3174.	137.707	132.610	122.416	2992.	0.077
5.200	0.059	49.11	3334.	144.968	139.613	128.903	2987.	0.081

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

	TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1
0	5.300	0.064	52.47	3500.	152.462	146.841	135.600	2983.	0.086
	5.400	0.069	55.98	3670.	160.184	154.290	142.503	2978.	0.091
	5.500	0.075	59.66	3844.	168.128	161.954	149.606	2973.	0.096
	5.600	0.081	63.52	4023.	176.284	169.823	156.901	2968.	0.102
	5.700	0.088	67.56	4206.	184.644	177.889	164.380	2962.	0.108
	5.800	0.095	71.77	4393.	193.195	186.140	172.032	2957.	0.114
	5.900	0.102	76.17	4582.	201.924	194.564	179.846	2951.	0.120
	6.000	0.110	80.76	4775.	210.816	203.147	187.808	2945.	0.127
	6.100	0.118	85.54	4971.	219.854	211.871	195.905	2938.	0.133
	6.200	0.127	90.51	5168.	229.020	220.720	204.120	2932.	0.141
	6.300	0.136	95.68	5367.	238.294	229.674	212.435	2925.	0.148
	6.400	0.146	101.04	5580.	247.675	238.714	220.792	2918.	0.156
	6.500	0.157	106.62	5800.	257.132	247.817	229.186	2911.	0.164
	6.600	0.168	112.42	6022.	266.628	256.958	237.616	2903.	0.172
	6.700	0.179	118.43	6243.	276.138	266.112	246.059	2896.	0.181
	6.800	0.191	124.66	6465.	285.634	275.253	254.489	2888.	0.190
	6.900	0.204	131.11	6685.	295.089	284.353	262.882	2880.	0.199
	7.000	0.217	137.78	6904.	304.473	293.386	271.212	2871.	0.209
	7.100	0.232	144.65	7120.	313.756	302.322	279.453	2863.	0.219
	7.200	0.246	151.74	7333.	322.910	311.133	287.579	2854.	0.229

7.300	0.262	159.03	7543.	331.904	319.790	295.564	2846.	0.240
7.400	0.278	166.53	7748.	340.710	328.267	303.381	2837.	0.251
7.500	0.295	174.23	7948.	349.299	336.535	311.007	2828.	0.262
7.600	0.313	182.12	8142.	357.644	344.568	318.415	2818.	0.274
7.700	0.332	190.20	8330.	365.719	352.341	325.584	2809.	0.286
7.800	0.351	198.45	8512.	373.499	359.830	332.491	2800.	0.298
7.900	0.371	206.89	8686.	380.962	367.013	339.115	2790.	0.311
8.000	0.393	215.49	8851.	388.085	373.869	345.439	2781.	0.324
8.100	0.414	224.25	9009.	394.850	380.381	351.445	2771.	0.337
8.200	0.437	233.15	9158.	401.240	386.533	357.119	2761.	0.351
8.300	0.461	242.20	9297.	407.241	392.309	362.446	2752.	0.364
8.400	0.486	251.39	9428.	412.840	397.700	367.418	2742.	0.379
8.500	0.511	260.69	9549.	418.029	402.695	372.025	2732.	0.393
8.600	0.538	270.11	9660.	422.801	407.287	376.261	2722.	0.408
8.700	0.565	279.63	9761.	427.149	411.474	380.123	2713.	0.422
8.800	0.594	289.25	9852.	431.073	415.251	383.607	2703.	0.438
8.900	0.623	298.95	9933.	434.573	418.620	386.714	2693.	0.453
9.000	0.654	308.73	10005.	437.650	421.582	389.447	2684.	0.468
9.100	0.685	318.57	10067.	440.309	424.142	391.809	2674.	0.484
9.200	0.717	328.47	10119.	442.557	426.306	393.805	2665.	0.500
9.300	0.751	338.42	10162.	444.401	428.082	395.443	2655.	0.516
9.400	0.785	348.40	10195.	445.851	429.478	396.732	2646.	0.533
9.500	0.820	358.41	10220.	446.919	430.506	397.681	2637.	0.549
9.600	0.857	368.44	10236.	447.616	431.177	398.301	2628.	0.566
9.700	0.894	378.48	10243.	447.955	431.505	398.603	2619.	0.582
9.749	0.913	383.41	10244.	447.996	431.544	398.640	2614.	0.591
LOCAL PRESSURE MAX DETECTED								
9.800	0.932	388.53	10243.	447.952	431.502	398.602	2610.	0.599
9.900	0.972	398.57	10235.	447.621	431.184	398.309	2601.	0.616
10.000	1.012	408.60	10220.	446.977	430.565	397.739	2592.	0.633
10.100	1.054	418.61	10198.	446.037	429.660	396.906	2583.	0.650
10.200	1.096	428.60	10169.	444.817	428.486	395.825	2575.	0.667

10.300	1.139	438.56	10134.	443.333	427.058	394.508	2566.	0.685
10.400	1.184	448.47	10093.	441.600	425.391	392.972	2558.	0.702
10.500	1.229	458.35	10047.	439.637	423.501	391.231	2550.	0.719

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE   IBHVG2.505   DATE   TIME

	TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1
0	10.600	1.275	468.18	9996.	437.458	421.404	389.298	2541.	0.737
	10.700	1.323	477.95	9940.	435.078	419.115	387.187	2533.	0.754
	10.800	1.371	487.67	9880.	432.514	416.647	384.913	2525.	0.771
	10.900	1.420	497.33	9816.	429.781	414.017	382.488	2517.	0.789
	11.000	1.470	506.92	9748.	426.892	411.237	379.925	2510.	0.806
	11.100	1.521	516.45	9677.	423.862	408.320	377.237	2502.	0.823
	11.200	1.574	525.90	9603.	420.704	405.281	374.435	2495.	0.841
	11.300	1.627	535.28	9521.	417.198	401.907	371.325	2487.	0.858
	11.400	1.681	544.56	9389.	411.555	396.476	366.317	2477.	0.871
	11.500	1.736	553.69	9231.	404.769	389.945	360.296	2467.	0.883
	11.600	1.791	562.66	9056.	397.282	382.739	353.651	2456.	0.894
	11.700	1.848	571.45	8870.	389.321	375.076	346.586	2445.	0.904
	11.800	1.906	580.05	8677.	381.038	367.103	339.234	2433.	0.912
	11.900	1.964	588.47	8478.	372.545	358.929	331.697	2422.	0.920
	12.000	2.023	596.68	8277.	363.930	350.637	324.051	2410.	0.927
	12.100	2.083	604.70	8075.	355.262	342.294	316.359	2397.	0.933
	12.200	2.144	612.52	7872.	346.597	333.954	308.668	2385.	0.939
	12.300	2.206	620.14	7671.	337.979	325.659	301.020	2373.	0.944
	12.400	2.268	627.57	7472.	329.445	317.445	293.445	2361.	0.948
	12.500	2.331	634.80	7275.	321.030	309.346	285.978	2348.	0.953
	12.600	2.395	641.84	7085.	312.852	301.474	278.719	2336.	0.956
	12.700	2.460	648.69	6899.	304.923	293.843	271.682	2324.	0.960
	12.800	2.525	655.37	6720.	297.241	286.449	264.864	2313.	0.964
	12.900	2.591	661.88	6546.	289.801	279.288	258.261	2301.	0.967

13.000	2.657	668.21	6378.	282.597	272.354	251.869	2290.	0.970
13.100	2.725	674.39	6215.	275.625	265.644	245.681	2278.	0.973
13.200	2.792	680.40	6058.	268.878	259.150	239.693	2267.	0.976
13.300	2.861	686.27	5905.	262.350	252.867	233.900	2256.	0.979
13.400	2.930	691.99	5758.	256.035	246.788	228.294	2245.	0.982
13.500	2.999	697.56	5615.	249.925	240.907	222.872	2235.	0.984
13.600	3.069	703.00	5476.	243.961	235.167	217.579	2224.	0.986
13.700	3.140	708.30	5339.	238.091	229.517	212.370	2214.	0.988
13.800	3.211	713.47	5205.	232.362	224.003	207.285	2203.	0.990
13.900	3.282	718.51	5075.	226.785	218.635	202.336	2192.	0.991
14.000	3.354	723.43	4948.	221.365	213.419	197.526	2182.	0.993
14.100	3.427	728.22	4825.	216.102	208.353	192.855	2172.	0.994
14.200	3.500	732.89	4706.	210.995	203.437	188.323	2161.	0.995
14.300	3.574	737.45	4590.	206.040	198.669	183.926	2151.	0.996
14.400	3.647	741.90	4478.	201.236	194.045	179.662	2141.	0.997
14.500	3.722	746.23	4369.	196.578	189.562	175.529	2131.	0.997
14.600	3.797	750.47	4264.	192.063	185.216	171.522	2121.	0.998
14.700	3.872	754.60	4161.	187.687	181.004	167.638	2111.	0.998
14.800	3.948	758.63	4062.	183.445	176.921	163.873	2102.	0.999
14.900	4.024	762.57	3966.	179.333	172.963	160.224	2092.	0.999
15.000	4.100	766.41	3873.	175.347	169.127	156.687	2083.	0.999
15.100	4.177	770.16	3783.	171.483	165.408	153.258	2073.	1.000
15.200	4.254	773.83	3695.	167.738	161.803	149.934	2064.	1.000
15.300	4.332	777.41	3610.	164.106	158.308	146.711	2055.	1.000
15.400	4.410	780.91	3528.	160.584	154.918	143.586	2046.	1.000
15.467	4.462	783.20	3475.	158.300	152.720	141.559	2040.	1.000
PROPELLANT 1 BURNED OUT								
15.500	4.488	784.33	3448.	157.169	151.631	140.555	2037.	1.000
15.600	4.567	787.68	3371.	153.865	148.451	137.623	2028.	1.000
15.700	4.645	790.95	3296.	150.669	145.375	134.787	2019.	1.000
15.800	4.725	794.14	3224.	147.578	142.400	132.044	2011.	1.000

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

	TIME (MS)	TRAV (M)	VEL (M/S)	ACC (G)	BREECH PRESS (MPA)	MEAN PRESS (MPA)	BASE PRESS (MPA)	MEAN TEMP (K)	FRAC BURN 1
0	15.900	4.804	797.27	3154.	144.586	139.520	129.389	2002.	1.000
	16.000	4.884	800.33	3087.	141.689	136.732	126.818	1994.	1.000
	16.100	4.964	803.32	3021.	138.883	134.032	124.328	1986.	1.000
	16.200	5.045	806.26	2957.	136.165	131.415	121.916	1978.	1.000
	16.300	5.126	809.13	2896.	133.531	128.880	119.578	1970.	1.000
	16.400	5.207	811.94	2836.	130.977	126.422	117.312	1962.	1.000
	16.500	5.288	814.69	2778.	128.500	124.038	115.114	1954.	1.000
	16.600	5.370	817.39	2722.	126.097	121.725	112.982	1947.	1.000
	16.700	5.451	820.03	2668.	123.766	119.481	110.913	1939.	1.000
	16.800	5.534	822.62	2615.	121.502	117.303	108.905	1932.	1.000
	16.900	5.616	825.16	2563.	119.305	115.188	106.954	1925.	1.000
	17.000	5.699	827.65	2514.	117.170	113.134	105.060	1917.	1.000
	17.100	5.782	830.09	2465.	115.097	111.138	103.220	1910.	1.000
	17.200	5.865	832.48	2418.	113.081	109.198	101.432	1903.	1.000
	17.300	5.948	834.83	2372.	111.122	107.313	99.693	1897.	1.000
	17.400	6.032	837.13	2328.	109.217	105.479	98.003	1890.	1.000
	17.500	6.115	839.40	2284.	107.364	103.696	96.359	1883.	1.000
	17.600	6.199	841.62	2242.	105.562	101.961	94.759	1876.	1.000
	17.700	6.284	843.79	2201.	103.807	100.272	93.203	1870.	1.000
	17.800	6.368	845.93	2161.	102.100	98.629	91.687	1863.	1.000
	17.900	6.453	848.03	2122.	100.437	97.029	90.212	1857.	1.000
	18.000	6.538	850.10	2084.	98.818	95.470	88.775	1851.	1.000
	18.100	6.623	852.12	2048.	97.240	93.952	87.376	1845.	1.000
	18.200	6.708	854.11	2012.	95.703	92.473	86.012	1838.	1.000
	18.300	6.794	856.07	1977.	94.205	91.031	84.682	1832.	1.000
	18.354	6.840	857.11	1958.	93.413	90.269	83.980	1829.	1.000

PROJECTILE EXIT

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

CONDITIONS AT:	PMAX	MUZZLE
TIME (MS):	9.749	18.354
TRAVEL (M):	0.9128	6.8400
VELOCITY (M/S)	383.41	857.11
ACCELERATION (G):	10244.	1958.
BREECH PRESS (MPA):	447.9955	93.4133
MEAN PRESS (MPA):	431.5436	90.2688
BASE PRESS (MPA):	398.6397	83.9798
MEAN TEMP (K):	2614.	1829.
Z CHARGE 1 (-):	0.591	1.000

ENERGY BALANCE SUMMARY	JOULE	%
TOTAL CHEMICAL:	56586656.	100.00
(1) INTERNAL GAS:	34086580.	60.24
(2) WORK AND LOSSES:	22500076.	39.76
(A) PROJECTILE KINETIC:	18327256.	32.39
(B) GAS KINETIC:	1545958.	2.73
(C) PROJECTILE ROTATIONAL:	144706.	0.26
(D) FRICTIONAL WORK TO TUBE:	0.	0.00
(E) OTHER FRICTIONAL WORK:	718397.	1.27
(F) WORK DONE AGAINST AIR:	66574.	0.12
(G) HEAT CONVECTED TO BORE:	1697185.	3.00
(H) RECOIL ENERGY:	0.	0.00

LOADING DENSITY (KG/M3):	838.404
CHARGE WT/PROJECTILE WT:	0.253

PIEZOMETRIC EFFICIENCY: 0.465
EXPANSION RATIO: 6.836

1GREEN GUN TEST CASE - M30A1 19P PERFORMANCE IBHVG2.505 DATE TIME

PARAMETRIC VARIABLES: / 1/	PROP	1	CHWT	CHWT (KG)
/ 2/	OUT	1	LDEN	L/D (G/CC)
/ 3/	PROP	1	WEB	WEB(MM)
/ 4/	OUT	1	PMAX	PMAX (MPA)
/ 5/	OUT	1	VMUZ	VMUZ (M/S)
/ 6/	OUT	1	ZMUZ(1)	Z @ EXIT
/ 7/	OUT	1	X@BO(1)	X @ B.O.

	/ 1/	/ 2/	/ 3/	/ 4/	/ 5/	/ 6/	/ 7/
0	12.500	0.83840	3.0168	448.00	857.11	1.0000	4.4097
	12.750	0.85500	3.0966	448.00	862.41	1.0000	4.7334
	13.000	0.87160	3.1791	448.00	867.33	1.0000	5.1440
	13.250	0.88821	3.2643	448.00	871.55	1.0000	5.5614
	13.500	0.90481	3.3527	448.00	875.17	1.0000	6.0699

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13. ABSTRACT *(Maximum 200 words)*

This work demonstrates the first phases of a newly proposed gun propellant formulation process that will minimize life-cycle costs through science-based design. This new approach proposes maximal use of modeling and simulation in the earliest phases of the developmental cycle to screen candidate formulations, resulting in elimination of probable poor performers and identification of the most promising test candidates. The screening and identification of propellant formulations are demonstrated under the assumption of a specific weapon platform and user requirements. The process of selecting a propellant for the assumed gun system application has been distilled into measurable steps, leading from a set of candidate materials, through logical and numerical filters, to a shorter list of energetic materials demonstrated as viable weapon platform choices. Environmental filtering and performance modeling are used to screen propellants through a well-defined sequence of tests designed to weed out materials not meeting safety, energy, or manufacturability standards. Because much of the testing is performed by computer modeling, the gun systems and energetic materials need not be present (or even existent) in order to be described and matched against performance requirements for future applications. The calculations demonstrate that utilizing computer models rather than physical testing in the early developmental stages of the formulation process can produce enormous savings in labor, material, and environmental costs, along with a tremendous reduction in the time required to select a "best candidate" propellant.

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propellant, cost minimization, gun, performance

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